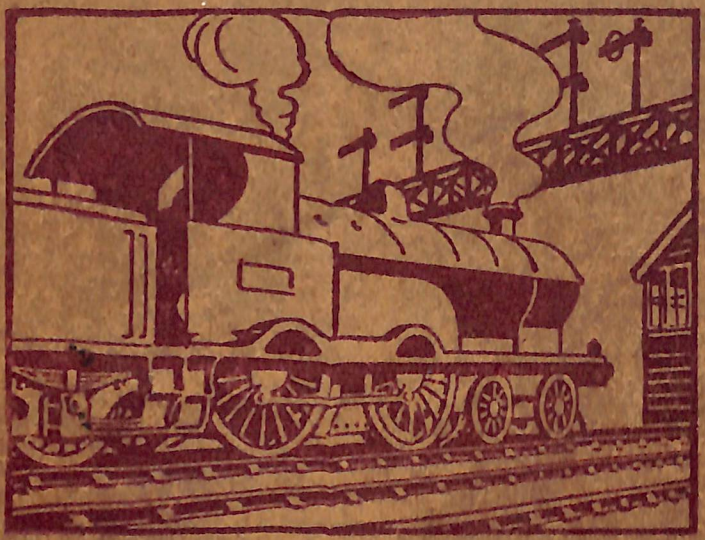
The Steam Locomotive



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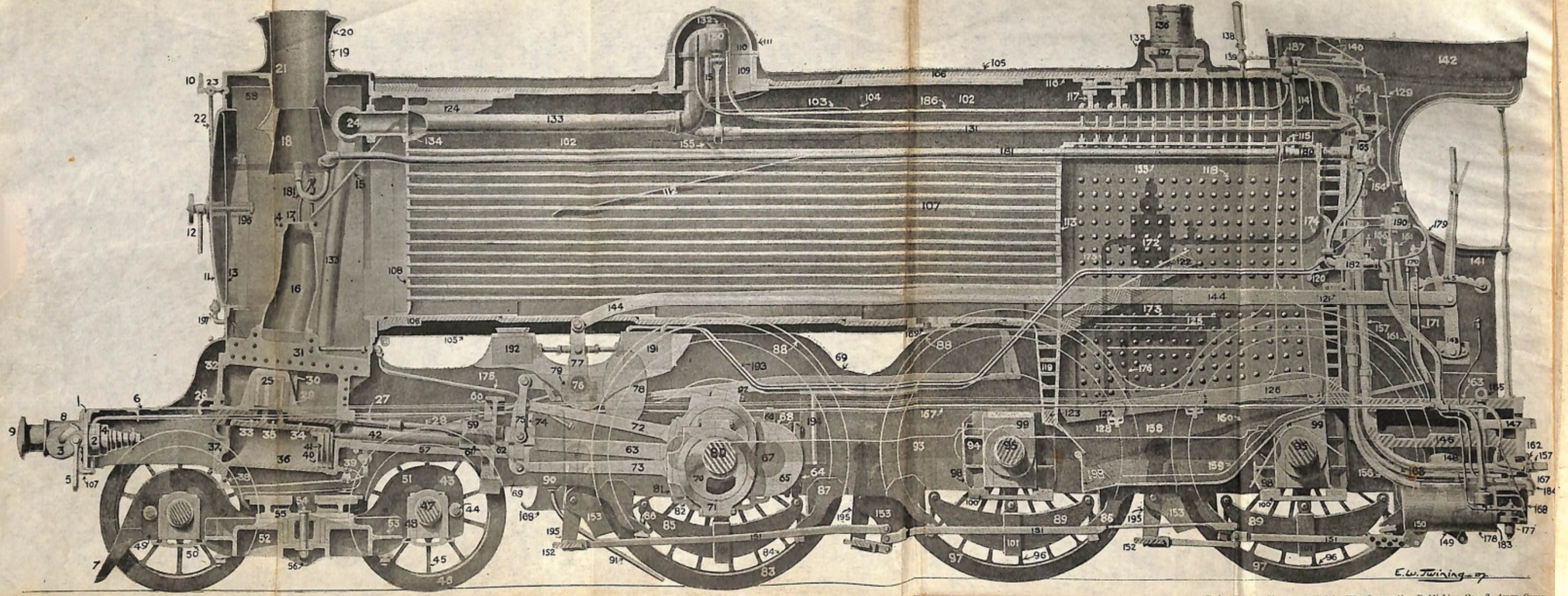
THE
STEAM RAILWAY LOCOMOTIVE



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ENGINE.

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THE STEAM RAILWAY LOCOMOTIVE

EXPLAINING THE COMPONENT PARTS AND METHOD OF WORKING OF MODERN STEAM RAILWAY LOCOMOTIVES

BY

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PREFACE

THE aim of this volume is to describe the chief parts of a modern locomotive and their functions in a manner which will prove useful to the engineering student and others who are interested. Within the limits of the space available the reasons which have led to the adoption of some of the principal parts have been added.

The descriptive chapters deal with the boiler and its more important adjuncts; the engine, including the mechanism and valve gear; the carriage and framing; and the tender. Chapters on compounding and superheating have also been added, which it is hoped will make these portions of the subject intelligible.

Considerations of space have made it impossible to touch more than the fringe of the subject, and the author is aware that there are many omissions of details which in a larger book would receive extended consideration. In so far as the construction of the component parts is concerned, the subject has been amplified in a companion volume, *Steam Locomotive Construction and Maintenance*.

The author desires to express his indebtedness for the use of photographs and blocks to Sir Henry Fowler, K.B.E., Chief Mechanical Engineer of the Midland Railway, Derby; The North British Locomotive Co., Ltd., Glasgow: The Superheater Corporation, Ltd., London; Messrs. Gresham & Craven, Ltd., Manchester; and to The Locomotive Publishing Co., Ltd., London, for the use of the folding plate.

E. L. A.

NOTTINGHAM.
September, 1920.

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THE STEAM RAILWAY LOCOMOTIVE

CHAPTER I

INTRODUCTORY

Principal parts of the Locomotive—Locomotive Types.

THE principal parts of the locomotive are:

(1) The boiler in which the fuel is burnt, and the resulting heat utilized for the generation of steam.

(2) The engine proper, which converts the energy of the steam into mechanical work.

(3) The framing and carriage, which form the foundation upon which the boiler and engine are carried, and serve to transmit the tractive force at the driving wheels to the coupling or "draw-bar," which connects the engine to the train.

(4) The tender, or in the case of a "tank engine" the tanks and coal bunkers, which carry the necessary supplies of fuel and water.

The boiler consists of three main portions; (*a*) the fire-box, a rectangular chamber at the back end, in which the fuel is burnt; (*b*) the barrel or cylindrical portion containing a large number of tubes, through which the burning products of combustion pass, and in their passage heat the water surrounding the tubes; and (*c*) the smoke-box, into which the waste gases from the tubes pass on their way to the chimney, the latter being placed on the top of the smoke-box. The smoke-box also

contains the blast pipe, out of which the exhaust steam from the cylinders issues up the chimney with considerable force, and thus creates the necessary draught through the tubes and fire-box.

The engine includes the cylinders, in which the steam acts upon the pistons, and imparts a reciprocating motion to them. Each piston rod is connected to a jointed piece known as the "crosshead," on which one end of the connecting rod is pivoted. The other end of the connecting rod revolves with and round the crank pin. The crank pins form part of the driving axle in an engine with inside cylinders, or are fixed in the bosses of the wheels in an outside cylinder engine. The reciprocating motion of the pistons is thus converted into the rotary motion of the wheels. The "engine" also includes the necessary valve gear and reversing motion.

The "carriage" includes the frames, springs, axles and wheels, with the buffer beams and draw-gear at both ends. The general functions of these need no explanation until their details are considered subsequently.

Types and Wheel Arrangements.

Locomotives are divided into various types and classes. The first main division may be that made between tender and tank engines, in which the former carry the coal and water in separate tenders, and the latter, which are used for shorter distance traffic, are provided with water tanks and coal bunkers, fixed on the framing of the engines themselves.

Further, there are engines for passenger and goods trains. This division is now to some extent an arbitrary one, since many engines are built which are capable of and are utilized for working both services, and it is quite usual for an engine to work an express passenger train in one direction, and return with a fast goods train in the other. For

many years there has existed on some railways a type of tender engine known as the "mixed traffic" engine, which has been specially built for stopping passenger trains and general goods service. The only type now confined exclusively to one service is the heavy mineral engine with eight coupled wheels, which is employed only for slow moving heavy goods or coal train traffic.

The modern system of classification is made in accordance with the various wheel arrangements of the engines. Fig. 1 (frontispiece) represents a large six wheels coupled express engine, built by the Caledonian Railway, at the St. Rollox Works, Glasgow, to the designs of the late chief locomotive engineer, Mr. J. F. McIntosh. This engine has inside cylinders, the six coupled wheels being placed at the rear, and a four-wheeled bogie carries the engine at the leading end. Such an engine is now known as a 4–6–0 type, the figure 4 representing the four wheels of the bogie, whilst the figure 6 stands for the six coupled wheels. The addition of the 0 at the end of the class designation means that there are no carrying wheels behind the coupled wheels. Had the engine been provided with a small pair of carrying wheels at the back, the designation of the type would have been 4–6–2. This system of classification is of American origin, and is a very convenient method of describing the "wheel arrangement" of an engine.

The number of types of engine, as regards wheel arrangement alone, is now very large, and ranges from small four-wheeled tank engines of the 0–4–0 type to large heavy engines having the 4–8–4 wheel arrangement, the latter representing an engine with a four-wheeled bogie at each end, and eight coupled wheels in the middle. The most usual form of passenger and express engine in this country is of the 4–4–0 type, *i.e.*, a leading bogie followed by four coupled wheels. For goods traffic an engine with

only six wheels, all coupled together, is the standard British design. This is known as the 0–6–0 type, the cyphers denoting that there are no uncoupled carrying wheels at either end. Of late years many larger engines have been constructed with the 2–6–0 and 4–6–0 wheel arrangements, the former for fast goods traffic, and the latter for both fast goods and express passenger trains.

Cylinder Arrangements.

The ordinary locomotive has two cylinders which may be either inside or outside the frames (*see* Figs. 4 and 5), and are usually placed at the smoke-box end, though there are some continental locomotives in which the cylinders are situated further back towards the middle of the engine. Of late years, in order to avoid extremely large cylinders, and to divide the straining actions, three and four cylinders have come into favour. In the case of 3-cylinder engines, one cylinder is placed inside, and the other two outside to obtain the necessary symmetry. In 4-cylinder engines, there are two inside and two outside cylinders.

In the following chapters frequent reference will be made to the plate Fig. 1, in which the various parts of the locomotive have reference numbers allotted to them, and in the following description these reference numbers will be used.

CHAPTER II

THE BOILER

THE description of the boiler not only includes the boiler barrel and fire-box, but also the smoke-box, ash-pan, and all other portions connected with the steam generating apparatus of the engine, with the exception of the superheater, which is described in Chapter IX. Only a certain number of engines are equipped with superheaters, which are of quite recent date as far as the locomotive is concerned. The engine shown in Fig. 1 is not furnished with a superheater.

Boiler Barrel and Tubes

The barrel of the boiler (102) consists of a long cylindrical shell or vessel, the diameter of which, in British engines, varies from about 4 ft. to 5 ft. 6 ins. and the length from about 10 ft. to 16 ft. 6 ins. It is made of steel plates of a thickness of $\frac{7}{16}$ in. in the smallest to $\frac{5}{8}$ in. and $\frac{11}{16}$ in. in the largest boilers, the thickness of plates depending principally upon the steam pressure as well as upon the diameter.

The barrel is made in two or three rings, which are riveted together transversely, each ring being bent round and held by rows of rivets arranged longitudinally. The longitudinal joints, where the two ends of a plate are bent round to meet, are made with butt strips, *i.e.*, short, narrow plates placed both above and below the joints. The plate thus forms a true circle. If the ends of the plate merely lap over one another, they do not form a circle, and are continually in a state of stress, since the steam pressure is all the time trying to force the barrel into a circular form.

The steam pressure about 30 years ago was generally

140 lb. per sq. in., but now lies between the limits of 170 and 225 lbs. per sq. in. Engines fitted with superheaters do not as a rule carry such high pressures, since the increased efficiency obtained from superheated steam permits of a reduction in the pressure, which in these engines varies between 160 and 200 lbs. per sq. in.

The barrel of the boiler contains a large number of flue tubes (107) of a diameter varying from $1\frac{5}{8}$ in. to $2\frac{1}{4}$ ins. outside. Their number may be anything from about 170 to 280, and depends upon the diameter of the boiler and the size of the tubes used. In the smaller boilers of 4 ft. diameter the tubes are generally from $1\frac{5}{8}$ in. to $1\frac{7}{8}$ in. diameter and 10 to 11 ft. long. In long boilers, the friction of the gases through such small tubes would be excessive, hence tubes of $2\frac{1}{4}$ ins. outside diameter are generally employed in such cases.

The object of the tubes is to provide a large heating surface, through which the hot gases coming from the fire-box transmit their heat to the water surrounding the tubes. The tubes are of iron, steel, brass, or a hardened copper composition, and all these materials have their advantages and disadvantages. Steel is now generally employed, owing to its lower cost. The tubes are expanded tightly into the holes in the fire-box tube-plate (113) by means of special roller expanders, and at the other end into the steel smoke-box tube-plate (108).

Fire-box.

At the back end of the boiler is a large rectangular chamber or fire-box, bounded on the front by the tube-plate (113), and on the back by the door-plate (120). In addition to the tube and door-plates, there is a large plate which forms the fire-box crown or roof (115) and the sides. In British and European practice, the whole of the plates forming the fire-box are of best copper, but in American engines they are

invariably of a special quality of mild steel, and the plates are not so thick. The preference of European engineers for copper fire-boxes is due to two causes ; firstly, copper is a better conductor of heat, secondly, this metal stands the straining actions due to repeated expansion and contraction better than steel. Steel does not " give " sufficiently, and has a tendency to crack, more especially in the corners. The flat surfaces of the fire-box are, as regards shape, the least able to withstand the pressure of the steam, and therefore they have to be supported at small intervals by means of *stays*. The roof-stays (114) consist of steel bolts screwed at both ends. The lower ends are screwed into the roof of the fire-box, and the upper ends into an extension of the boiler barrel, known as the " fire-box shell," or " outside fire-box." The wrapper plate of the fire-box shell, which is made of steel plates like the boiler, surrounds the fire-box on the two sides, the back, and the top.

The four front rows of roof-stays (117), it will be noticed, are different in form from the other roof-stays. These front rows are expansion stays, and are designed to allow the front portion of the fire-box to expand vertically under the effect of the heat. If the stays were rigid, the irresistible force of expansion would cause the fire-box to bend and crack at the top corners, and the tubeplate (113) would have the tube-holes distorted.

The sides and back of the fire-box shell are placed much closer than the roof-plate to the copper fire-box plates, a water space of about 3 ins. being left between them. This water space is clearly shown at the back, and there is a similar but shorter water space (119) at the front. In these water spaces there are also shown the short stays (119) which stay the fire-box to the shell. The heads of the similar stays in the sides are seen at 118. These stays are spaced at regular intervals of about 4 ins. both in the vertical and horizontal directions, and prevent the flat sides

of the fire-box from being crushed in by the enormous pressure. Few people, other than those engaged in locomotive engineering, have any idea of the large amount of this pressure. In a fire-box 7 ft. 6 ins long by 3 ft. 4 ins. wide, the area of the roof is 3,600 sq. inches. and assuming the sides of the fire-box to be vertical, which, however, is not generally the case, the total vertical pressure on the roof, with a boiler pressure of 200 lbs. per sq. inch, is then $3,600 \times 200 = 720,000$ lbs., or about $321\frac{1}{2}$ tons. This gives some idea of the load which the roof-stays have to support. If the depth of the fire-box be 6ft. the side-stays have to support a total presure of $\frac{90 \times 72 \times 200}{2240}$ = nearly 579 tons. There are, however, a very large number of stays, and as they are spaced at 4 in. intervals in both directions, each stay supports an area of $4 \times 4 = 16$ sq. ins., and the load on each stay is therefore 3,200 lbs. If the stays be $\frac{7}{8}$ in. diameter at the bottom of the screw threads, the effective sectional area is 0·6 sq. in., and the stress is nearly 2·39 tons per sq. in. Taking the ultimate tensile strength of copper when hot to be 12 tons per sq. in., there is a factor of safety of 12/2·39 = 5.

The side-stays suffer specially severely under the effects of the expansion of the inside fire-box. When steam is being raised the inside fire-box becomes much hotter than the outside shell to which it is united by means of the stays. Moreover, being of copper, its co-efficient of expansion is greater than that of the steel shell. The result is that the walls expand and rise in a vertical direction, and the ends of the stays in the copper plate are forced above the level of the other ends in the steel plate, so that the stays are bent, more especially those in the top rows of the fire-box. This alternate bending and unbending of the stays, coupled with the corrosion to which they are subject, causes them to break

requently. A constant watch has to be kept on the fire-box and stays, for they are an unceasing source of trouble. In fact the engine itself, compared with the boiler, requires comparatively little attention.

The side-stays of a locomotive fire-box are in British practice made from best rolled copper bars from $\frac{7}{8}$ in. to $1\frac{1}{8}$ in. diameter, the usual size being 1 in. They are screwed into the copper fire-box plate at one end, and into the steel shell plates at the other, both the projecting ends being riveted over to form heads, as an additional security against pulling out from the plates. In American practice the stays are invariably of the very best soft iron or steel, and soft steel stays are coming into use to a large extent in this country, even in conjunction with copper fire-boxes. Specially formed stays which have a ball and socket joint at the outside end, are also being tried in this country. These are largely used in America, and their advantage lies in the flexibility of the joint, which allows them to turn with the expansion instead of bending.

The copper fire-box is secured to the outer steel fire-box shell at the bottom by means of a cast-steel or wrought-iron frame, known as the foundation ring, of which a section is shown at 123. This is bent round to form a large rectangle which embraces the bottom of the fire-box. Long rivets are passed through both the steel and copper plates and firmly secure the foundation ring between them.

Smoke-box.

The front portion or extension of the boiler under the chimney is termed the smoke-box, and is separated from the boiler proper, which contains the water and steam, by the tubeplate (108). The smoke-box is a cylindrical chamber which contains the blast pipe (16), the bottom extension of the chimney or petticoat pipe (18), and a portion of the steam pipe (24 and 133). The smoke-box,

not being subjected to any pressure, is made of thin steel plates, the wrapper plate being united to the front or door plate, and to the front tubeplate by angle irons. In Fig. 1 the front tubeplate is, however, set back a certain distance inside the boiler. The bottom of the smoke-box is formed by the top portion of the cylinder casting (31), when the cylinders are inside. In outside-cylinder engines a box is built up of plates and angle irons, or formed of a steel casting, which extends between the frames. This box also serves the purpose of a stay to unite the frames on the two sides of the engine.

A large circular door is provided in the front of the smoke-box to provide for removing the ashes which accumulate at the bottom of the smoke-box, and also for introducing a long rod to clean the boiler tubes. The door (11) is dished to strengthen it, and is provided with a plate (13), fixed a short distance behind it, which protects the door from the heat. The door is fastened by means of a spindle or "dart," which passes through a crossbar (196), and is tightened by the hand wheel (12). It is absolutely essential that the door should be perfectly air-tight, so that there will be no leakage of air into the smoke-box, for should this occur the draught on the fire is defective, and any hot cinders that may be in the smoke-box will continue to burn, and thus damage the plates.

The blast pipe (16) is of cast iron and is provided with a nozzle (17) of restricted diameter. The blast pipe forms the outlet for the exhaust steam from the cylinders into the atmosphere, and the suction action of the steam, as it is forcibly expelled, creates the necessary draught on the fire, and pulls the hot gases and flame through the boiler tubes.

The Grate.

Returning again to the fire-box, the fire is carried on the grate bars (126), which are supported

by bearers (127). Below the grate bars is the ash-pan (158) formed of plates, and an angle iron framing (159). At the front there is provided a hinged door or "damper" (198), which can be raised and lowered from the foot-plate. This door serves to admit air under the grate which passes through the incandescent fuel. Many engines are also furnished with a door at the back of the ash-pan, as it is found very convenient under certain circumstances to work the engine with the front damper closed and that at the back open. A sloping brick arch (122) is fixed inside the fire-box as shown, and at the fire-hole (120) there is an iron deflector plate, the use of these being explained below.

When the fire is lighted, whilst the locomotive is in the engine shed, an artificial draught has to be created to enable it to burn up properly. This draught is supplied by means of a blower (14) fixed in the smoke-box. The blower consists of an iron tubular ring fitted round the top of the blast pipe nozzle, and has a number of holes drilled in the top side round the whole circumference. A small steam pipe is connected to the ring, so that when the driver opens the blower valve from the foot-plate, a series of small jets of steam issue through the holes in the ring, and being directed up the chimney cause the necessary draught.

Draught and Combustion.

When the engine is running the blower is not in use, the draught being provided by the much more powerful blast issuing from the blast pipe. The primary air for the combustion of the coal enters the ash-pan through the door (198) and is drawn through the incandescent fuel on the grate. A large volume of combustible gas, consisting principally of carbon monoxide (CO) and various hydrocarbons, is produced above the fuel, and in order to burn these properly, air must also be admitted

above the fire. This air enters through the fire-hole door, which is constructed specially for this purpose. If the door consists of two laterally sliding plates, they must be left partly open to admit air. Some doors are hinged at the bottom, so that they can swing downwards when opened : these are provided with a special latch and a notched sector so that they can be held open to any extent that is considered desirable, and the suitable quantity of air admitted. Other doors are cast hollow with passages through which the air can flow. When the air enters it strikes the deflector plate previously mentioned. This plate is in the form of a scoop with the hollow side underneath, and is inclined downwards in order to deflect the air towards the incandescent fuel, and enable it to mix with the gases. If however, matters were left in this condition, there would be a loss of heat owing to the gases passing straight to the tubes and being drawn through them before combustion had been properly completed. To avoid this, and to provide a more circuitous path for the gases the brick arch (122) is placed across the front end of the fire-box. The arch is made of fire-bricks supported on studs fixed in the sides of the fire-box, and is inclined upwards so that the tube openings are above it, and partially screened from the direct air current coming from the fire-hole door. By this means the lower portion of the fire-box is converted into a combustion chamber. The mixture of gases and air is deflected towards the lower front end of the fire-box, but before it can enter the tubes it is forced by the brick arch to return towards the back of the fire-box, whence it curls round the back edge of the arch on its way to the tubes. The result is that a longer and better admixture of the gases and air is obtained, and more nearly perfect combustion is secured. Moreover, the brick arch becomes heated to a very high temperature, and acts as a reservoir of heat. In

passing through the tubes, the gases part with their heat to the water, and finally enter the smoke-box, whence they are entrained up the chimney by the action of the blast.

Chimney, Regulator, and Safety Valves.

In very large engines, in which the boiler has to be pitched at a considerable height, the portion of the chimney outside the smoke-box is necessarily very short, otherwise the engine could not pass under the "loading gauge," that is the top of the chimney would be too high for the over bridges and tunnels. The chimney is therefore extended downwards inside the smoke-box, and is also provided with a "petticoat" (18). The petticoat pipe serves the purpose of producing a more equal draught spread over the whole of the tubes. Without it there is a tendency for the gases to be drawn through the top rows of tubes to the neglect of the bottom rows, and the water at the bottom of the boiler does not receive its necessary share of the heat.

The chimney itself is formed of an inner liner or the chimney proper (21), an outer casing (19) generally of cast iron, and a cap (20). The form of the cap is not purely ornamental; it has the additional object of cutting and deflecting the air, so that the issuing steam and gases can escape freely from the top.

On the centre of the boiler barrel is placed the *dome* (109), which has a removable cover (110). Inside the dome is placed the regulator (130), through which the steam is taken from the boiler to the cylinders. After entering the regulator the steam passes into the steam pipe (133), and through the T piece (24) where the pipe divides into two branches, which pass downwards, following the contour of the curved sides of the smoke-box, one branch to each of the two cylinders. The steam pipes are of copper; formerly they were made with a brazed joint or

seam, but now they are invariably solid drawn. Where superheated steam is employed the pipes are of steel, since copper is not a safe material for use with superheated steam.

The *regulator head* (130) contains a double beat valve, which is raised to admit steam by means of a vertical rod, attached at the bottom to a small eccentric, the latter being fixed on the long spindle or rod (131). This spindle terminates in the cab of the engine in passing through a gland fixed on the back plate of the fire-box shell, and on the end of it is fixed the regulator handle (129), which can be moved by the driver. In moving the handle the long rod (131) is rotated through an angle and thus moves the eccentric which in turn lifts the valve (132) in the regulator head. The height of this lift and the consequent amount of steam admitted to the steam pipe depends upon the distance through which the driver moves the handle.

The object of the dome is to provide a steam space at some distance above the level of the water in the boiler, so that steam as dry as possible may be admitted through the regulator to the cylinders. If the steam were collected near the level of the boiling water, a considerable amount of spray would be carried by the steam into the cylinders, where its presence is very harmful both in condensing the steam and in endangering the cylinders by its incompressibility.

Several eminent engineers object to the dome on the ground that the hole, which has to be cut for it in the boiler plate, weakens the latter, and many engines are built without domes. The steam is then collected in a long pipe at the top of the boiler, the pipe being provided with perforated holes or slits along its upper portion. The regulator in this case is generally placed in the smoke-box and bolted to the T-piece where the steam pipe bifurcates.

The *safety valves* (137) are placed on the top

of the fire-box shell. Formerly it was the practice to place them on the top of the dome, and their lift was controlled by means of a lever and spring balance. Such valves could, however, be tampered with, and this was occasionally done in the days when boiler pressures were much lower than they are now, and the drivers wished to raise the pressure in order to obtain more power. Such tampering would be very dangerous in these days of high steam pressures and, in order to ensure that the pressure does not exceed a predetermined limit, two to four safety valves are employed, and the precaution is taken of locking them up in a casing. In the engine illustrated by Fig. 1, this casing contains four valves, each about 3 ins. in diameter, and the lift is controlled by springs (136) which bear directly on the top of the valves.

Water Supply to Boiler. Injectors.

For delivering feed water to the boiler, force pumps were invariably used prior to the invention of the injector in 1858 by a French scientist, M. Henri Giffard. The pumps were driven either by an eccentric fixed on the driving axle, or directly from the crosshead of the engine. Such pumps have the disadvantage of supplying water to the boiler only when the engine is in motion, so that when the engine is stationary no water can be sent into the boiler, although the latter may be using up the limited supply contained within it. In former years, in order to fill the boiler of an engine prior to lighting up the fire, it was necessary to run the engine up and down the sidings at the engine shed by means of another locomotive already " in steam." Another defect of the pump, especially when driven from the crosshead, was that the inertia of the water caused such high pressures inside the pump and connecting pipes that bursts were not infrequent. With the injector these troubles do not exist, but

on the other hand, an injector will not take feed water at an initial temperature higher than 130° to 140°F., and only special injectors will work at temperatures as high as these.

The *injector* is an apparently paradoxical appliance which forces water into a boiler against the same pressure as that of the steam which is used to force it in. Briefly stated, the action of the injector depends upon the fact that a jet of steam issuing from a nozzle under pressure has a high velocity, much greater than the velocity of a jet of water issuing under the same pressure from the boiler. If the jet of steam unites and flows with a stream of cold water coming from a tank or other

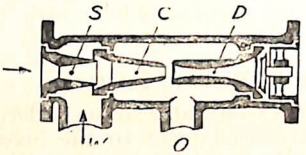


FIG. 2.—DIAGRAM OF INJECTOR.

source of supply, part of the steam is condensed, and imparts its velocity to the water. Although the steam has been condensed the velocity of the joint stream or jet has not been reduced to that of the jet of water, which would issue from the boiler under the same pressure, and therefore the former jet is able to overcome the latter, having greater momentum, and is able to lift the clack valve on the boiler and enter the latter.

Many improvements have been made in the injector since its first introduction. It now consists of three main portions, (Fig. 2), the steam nozzle S, the combining tube C, and the delivery tube D. In the early steam nozzles the steam jet spread laterally and part of the energy of the steam was lost. The nozzle was altered in form so that the

expansion of the steam was completed inside it, and the velocity of the issuing steam was thereby greatly increased. The water enters at W, and O is the overflow.

The combining tube is the portion in which the mixture of steam and water takes place, the water being drawn in at the point where the steam nozzle projects slightly into this tube. The combining tube is convergent, and narrows down to a smaller diameter as the area of the combined jet decreases with the condensation of the steam. The third portion or delivery tube narrows down near its inlet, and then diverges, *i.e.* increases in diameter towards the outlet. This allows the jet to increase in area, but in so doing its velocity (which is at its maximum when entering the delivery cone) is decreased. There is no loss of momentum in this, as the mass of the flowing jet, multiplied by its velocity, remains the same.

The elementary injector mentioned above will not lift the water when this is below the level of the instrument. This improvement was made by Giffard, who made the injector so that the outlet from the steam nozzle and the inlet to the combining tube were enclosed in a chamber, in which a vacuum was produced by the jet action of the steam. The condition required for creating a vacuum and thus lifting the water is that the diameter of the steam nozzle must be less than that of the tube through which the steam and air are exhausted, and Giffard reduced the steam nozzle area when and as required by means of a sharp pointed spindle, which was movable up and down inside the steam nozzle. When starting the injector the area of the nozzle was reduced in this manner, and as soon as water issued from the injector over-flow, showing that it had been lifted, the pointed spindle was drawn back, and the full area of the steam nozzle restored.

It was, however, soon found necessary to effect

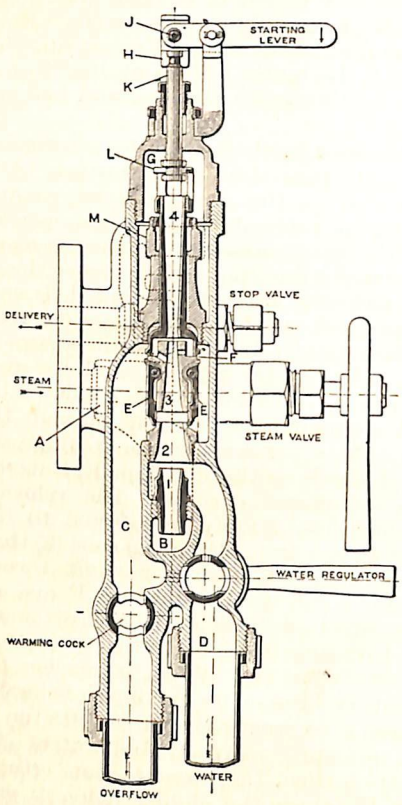
further improvements. The shock sustained by a locomotive when passing over junctions and crossings had a tendency to break the jet, so that the injector stopped working properly and did not feed the boilers. To re-start it, the fireman had again to adjust his nozzles, and as this occurred frequently, some method had to be found to make the re-starting of the injector automatic. This was accomplished by forming the combining cone in two portions 2 and 3 (*see* Fig. 3), with a small chamber between them which is closed by the flap valves E. When the injector has started the external atmospheric pressure keeps the flaps closed, (since there is a partial vacuum inside), and prevents the air from entering and breaking the jet. With excess of internal pressure the flaps will open and allow the steam and water to escape.

The water supply for the boiler is taken from the tender by means of two pipes with flexible couplings between the engine and tender. One of these *feed pipes*, as they are called, is shown in Fig. 1 at 157 as it enters under the footplate, from which point it curves upwards to the injector (154), which in this case is fixed on the fire-box shell plate inside the cab within reach of the fireman. There are always two injectors so that, in case one of them fails, the other is immediately available. If very hot water be used to feed the boiler, an independent steam driven pump is used instead of one of the injectors, since an injector cannot work with feed water at a temperature above about 130° to 140° F. Even with these temperatures, the injectors have to be of special design. An ordinary injector will only work reliably if the temperature of the water delivered to it does not exceed 110° F. to about 125° F., depending upon the boiler pressure. An increase in the height from which the water has to be lifted reduces the delivery capacity.

The temperature of the water delivered by the

injector to the boiler is considerably higher than that of the water which enters the ejector, since part of the heat of the steam is taken up. The water delivered to the boiler will be at 180° F. to 250° F., according to the boiler pressure and type of ejector used.

Fig. 3 shows a modern *hot water injector* by Messrs. Gresham & Craven, Ltd. (Manchester). An internal steam pipe from the dome conveys steam to the injector steam valve A, which, when opened, admits steam to the steam nozzle (1) by the passage B. The steam issuing from the nozzle opens the two side flaps E, and also lifts the sliding delivery cone 4, making an aperture at F, and passes out freely down the overflow pipe. In doing so, it creates a partial vacuum in the water pipe D, and the water rises to the injector. The water then coming into contact with the steam travels with it through the lifting cone (2) and in condensing the steam, a vacuum is created which closes the side flaps E, thus preventing air from entering the cones. The velocity of the steam being now largely transferred to the water, the latter passes from the lifting cone (2) through the combining cone (3). After passing through this, the jet flows out of the aperture F and down the over-flow pipe C until such time as it attains sufficient velocity to carry itself past this space, and enters the delivery cone (4). When it reaches this point the jet is travelling at its maximum velocity, and its momentum is so great that the jet lifts the " clack " or back pressure valve J, and enters the boiler. At the same time, the pressure thus created in the chamber G forces the sliding delivery cone down on to its seat, and closes the aperture F, shutting in the water which would otherwise be boiled off when the injector is working with hot water at 130° F. When the temperature of the water is below 100° F. the injector will work with the aperture F open, as in the ordinary cold water injector.



[*Gresham & Craven, Ltd.*

FIG. 3.—HOT WATER INJECTOR.

Water Level and Steam Gauges.

The water level in the boiler is indicated to the driver by the water-gauges (164) fixed on the fire-box shell inside the cab. The vertical glass tube of the gauge is fitted by means of special gland packings into two brass fittings bolted to the fire-box shell plate. These fittings have passages through them, the upper one communicating with the steam space, and the lower one with the water space ; taps are provided so that the passages may be closed when required. The steam enters the gauge glass from the top, and the water from the bottom, the level of the latter in the glass being the same as that in the boiler, so long as the passages in the fittings are unobstructed. The glass is protected by being enclosed in a cage of glass or wire. Should the glass burst, automatic ball valves in the fittings close both the steam and water passages.

Gauges to register the boiler pressure, and also the air pressure or vacuum for the brakes, are fixed on the boiler inside the cab. These are of the usual dial pattern with Bourdon tubes. There are also a number of other fittings and valves, which belong to the vacuum, or the Westinghouse compressed air brake, whichever is fitted to the engine. Some engines, such as the one illustrated in Fig. 1, are supplied with both brakes.

The boiler has to be thoroughly and regularly washed out, otherwise dirt and incrustation would accumulate. Such dirt and sediment cover the plates and tubes, and not only reduce their conductivity for heat, but also cause them to be overheated and burnt. Wash-out holes, such as the one (169) shown below the barrel of the boiler, are therefore provided, in addition to mud-holes at the bottom of the water space round the fire-box. These openings are provided with strong pressure-tight covers or doors, which can be removed when the boiler has to be washed out.

Boiler Fastenings and Clothing.

The fastening of the boiler to the engine frames has to be such as to allow of its free expansion, the boiler under steam being from $\frac{3}{16}$ in. to $\frac{5}{16}$ in. longer than when it is cold. The boiler is therefore fastened rigidly only at the front or cylinder end of the locomotive. At the fire-box end, expansion brackets (125) are riveted to the sides of the fire-box shell. These are in the form of angle irons, the bottoms of which rest upon the frame (but are not fastened to it), in such a way that they can slide freely on the frame, and move backwards as the boiler expands.

To reduce loss of heat by radiation, the boiler plates are clothed outside with a non-conducting material. Formerly strips of wood were used, which enclosed an air cushion between them and the boiler, but this form of lagging is obsolete on most railways, as the wood became charred, especially in the neighbourhood of the fire-box, and sometimes caught fire. Two modern forms of lagging (106) consist either of asbestos mattresses, or special blocks of a mineral non-conducting material, which are cut to fit the contour of the boiler. Finally a number of thin sheets of iron or steel (105) are placed over the lagging, and secured by bands and clips.

CHAPTER III

THE ENGINE

THE engine includes the cylinders, pistons and piston-rods, connecting rods and cranks, also the valves, valve gear and reversing motion. Strictly speaking, the crank or driving axle is an essential portion of both the engine and the vehicle.

The locomotive engine is similar in principle to most forms of stationary slide-valve, non-condensing steam engines, provided with reversing gear. The more complicated types of stationary engines, with Corliss and drop-valve gears, are not represented

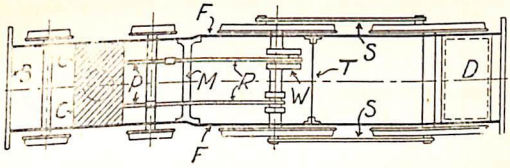


FIG. 4.
DIAGRAM (PLAN) OF ENGINE WITH INSIDE CYLINDERS.

in locomotive design ; a few such engines have been constructed in France and Germany, but being too complicated they have not been perpetuated.

Cylinders.

The cylinders of a locomotive may be placed either inside or outside the frames. Fig. 4 shows diagrammatically a plan view of the inside cylinder arrangement with crank axle, C being the cylinders, P the piston-rods, R the connecting rods, and S the coupling, or "side" rods. The same reference letters apply to Fig. 5 which represents an

outside cylinder engine. In this the crank axle is replaced by a straight axle, and the connecting rods work on pins outside the wheels. The plate (Fig. 1) shows an engine with inside cylinders (36), of which the illustration gives a section through the bottom half.

Inside cylinders have until recent years been greatly preferred by British locomotive engineers on two grounds. Firstly, the cylinders, being enclosed between the frames and immediately underneath the smoke-box, are less subject to loss of heat through radiation. Outside cylinders are exposed to a strong rush of air when running, and require very careful

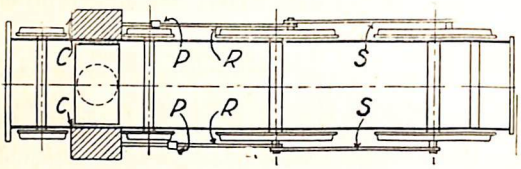


FIG. 5.
DIAGRAM (PLAN) OF ENGINE WITH OUTSIDE CYLINDERS.

covering with felt or lagging to reduce radiation losses. Secondly, inside cylinders are placed much closer together, and the action of the pistons, rods, and reciprocating parts causes much less swaying or "nosing" movement, hence steadier running is obtained than when outside cylinders are employed. One disadvantage of inside cylinders is that parts of the machinery or "motion" are not so accessible for oiling and examination, and this is one of the reasons why pits are always provided in locomotive sheds in this country to enable the enginemen, fitters and cleaners to get underneath. On the Continent outside cylinders are almost invariably employed, and in America inside cylinders are never

used in ordinary 2-cylinder locomotives, but there are a few 4-cylinder, balanced compound engines, in which one of the two pairs of cylinders is placed inside.

In spite of the deep-rooted British preference for inside cylinders, it had to be recognized that a limit was reached as the engines increased in size. With the standard 4 ft. 8½ ins. gauge between rails, the width between the inside frames of the engine cannot exceed 4 ft. 1 in. or 4 ft. 1½ in., and as the cylinders in successive types of engine increased in diameter, it became extremely difficult to find room for them and for the valves. Moreover, the webs, W (Fig. 4), of the crank axle became too narrow, and consequently not strong enough to transmit the greatly increased power required. For these reasons a large number of heavy engines are now built in this country with outside cylinders. This allows more room for the cylinders and valves, and the crank axle is dispensed with in favour of crank pins fixed in the outside of the driving wheels. The diameter of the cylinders in British engines varies from 16 ins. to 22 ins., and the stroke of the pistons is from 22 ins. to 30 ins. A stroke of 26 ins. is the most usual in practice. In America, where the "loading gauge" permits much larger engines to be used, larger cylinders are in use. The Caledonian engine, represented by Fig. 1, has cylinders 20 ins. diameter by 26 ins. stroke, and is considered a very large engine for this country.

The *cylinders* (36) are made of a special close-grained hard cast iron of the best quality, free from any honeycombing or porosity. They are carefully bored to gauge to the exact diameter required, except at the ends where the bore is slightly enlarged so that the piston at the ends of the stroke does not wear a ridge inside. Detachable covers (37) are fixed to each end by means of studs. The front covers are always removable to enable the pistons

to be withdrawn, but in some designs the back covers, which are provided with projections, to which the slide bars are fastened, are cast solid with the body of the cylinders. Inside cylinders were formerly cast separately, and the two faced flanges between them bolted together to make a solid joint, but in present-day practice both cylinders are cast in one piece. This involves a more expensive pattern, from which the casting is made, but saves a great deal of machine work. At each side the cylinders are bolted to the engine frames, the bolts being turned in order to fit the holes in both cylinders and frames, and then driven home a tight fit, since it is absolutely essential that there should be no slackness in the connection to the frames. Outside cylinders are always cast separately, and bolted to the outside of the frames.

The cylinder covers are made somewhat thinner than the body of the cylinders, so that, should any obstruction to the piston occur, the covers are broken without damage to the more expensive cylinders. For the same reason, a space of about $\frac{3}{8}$ in. is left between the covers and the piston, when the latter is at the extreme ends of its stroke. An excess of water in the cylinders is the usual cause of such breakages. Water is practically incompressible, and should the volume of water trapped between the piston and the cover exceed the volume of the "clearance space," the cover would be knocked out and broken.

To drain the cylinders from any water entering them or condensing therein, each cylinder is furnished with two cocks (38), one at each end. The cocks are connected together by a rod, and are worked by the lever 39, one arm of which is attached to a long rod. This rod terminates on the footplate in a lever handle (166), by pulling which the driver can open the cocks, so that the water is blown out by the steam in the cylinders.

The *pistons* (40) are generally of cast iron, but in order to lighten them, they are now frequently stamped out of mild steel. The diameter of the body of the piston is turned very slightly less than the bore of the cylinder, and in order to prevent any leakage of steam from one side of the piston to the other, it is fitted with spring rings (41). These consist of cast iron rings about $\frac{1}{2}$ in. broad, turned slightly larger than the bore of the cylinder, and then split with a saw. The piston has two grooves turned all round its circumference, into which the rings are sprung. When in place in the cylinder, the rings "spring" outwards, forming a perfectly tight fit between them and the cylinder walls.

The *piston-rod* (42) of steel is either screwed into the body of the piston, or turned with a conical end, which is tightened into the piston by means of a large nut.

The cylinders are provided with *ports* (33 and 34) at each end for the admission and exhaust of the steam. These ports, which are 15 ins. or 16 ins. long by about 1 in. wide, curve backwards (Fig. 10) and open out on a planed surface on which the *slide valve* moves backwards and forwards. The slide valve is enclosed in the steam chest into which the steam from the boiler enters from the pipe 133 (Fig. 1). The valves are made of gun metal in British practice, and of cast iron in American locomotives, and are enclosed in a wrought iron frame which forms part of the valve spindle (27 and 28) driven by the eccentrics and link motion. The valves in a British engine with inside cylinders, and having the Stephenson link motion, are very frequently placed vertically in the steam chest which is situated between the two cylinders, but they may be placed at any angle. In engines with large cylinders there is only a limited amount of space available, and the valves are therefore often placed above or below the cylinders.

Piston-rods Slide Bars and Connecting Rods.

The piston-rod (42, Fig. 1) is connected at the end furthest from the cylinder to a block termed the crosshead (61), which is fitted with top and bottom shoes or slide-blocks. The shoes work between the slide or guide-bars (57), the object of this arrangement being to keep the piston-rod exactly in line with the centre line of the cylinders. The crosshead also provides a joint, to which the small or front end of the connecting rod (63) is attached. The arrangement is shown in the diagram Fig. 6, in which

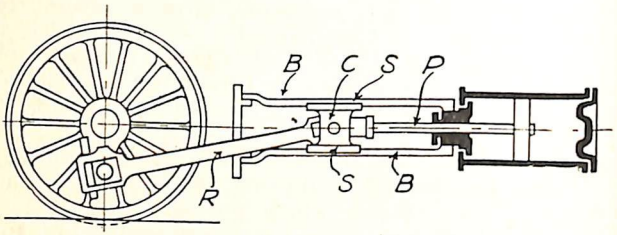


FIG. 6.—DIAGRAM OF ENGINE MECHANISM.

P is the piston-rod, C the crosshead, and R the connecting rod. BB are the slide bars, one above and one below, and attached to the crosshead are the slide blocks SS, the channelled surfaces of which move along the slide bars. (*See also* Fig. 17.)

The *slide bars* may be either two or four in number. The engine in Fig. 1 has four bars, although to avoid complicating the drawing only one is shown. In this arrangement there are two bars at the top above the crosshead, one on each side of the centre line of the piston-rod, and two similarly placed at the bottom. When two bars only are used, their width is greater, and they are placed centrally one above, and the other below the crosshead. In some engines only one slide bar above the crosshead

is used, in which case the slide block is made to embrace the bar.

At the front or cylinder end, the slide bars are bolted to projections or lugs cast on the back cylinder cover, and at the back they are secured to a transverse steel casting (60) termed the " motion plate." The latter extends right across the engine and is riveted to the frames on each side, so that it serves, not only to carry the slide bars, but also as a rigid stay to keep the frames at the proper distance apart. The guides for the valve spindles (59) also form part of the motion plate casting, and take the shape of long projections which are bored to fit the valve spindles.

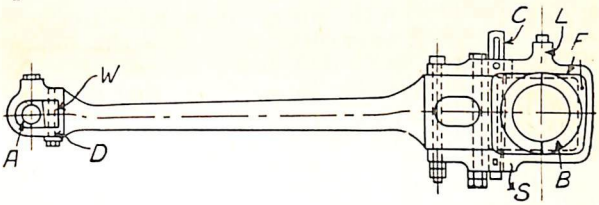


FIG. 7.—CONNECTING ROD.

The *connecting rod* (63) forms the connection between the end of the piston-rod and the crank, and consists of a flat rod of rectangular section, the depth of which increases gradually from the crosshead or " small end," to the crank or " big end." The two ends of the rod are made to a considerable number of different designs, of which Fig. 7 shows one form. The small end is provided with either a circular bush or a small brass (A) as shown, the hole in which accommodates the pin forming a portion of the crosshead. The brass (A) is in two portions, and is provided with a wedge (W) to take up the wear by screwing up the bolt (D). The " big end " has a large brass (B) which embraces the

" crank pin," forming part of the crank axle (*see* 67, Fig. 1). The large solid portion of the rod butts against the front portion of the brass, and both the end of the rod and the two portions of the brass are enclosed inside a three-sided piece (S), somewhat rectangular in shape, known as the " strap." The strap is firmly secured to the body of the rod by two large bolts. The long cotter (C) behind the second bolt is for the purpose of moving the front part of the brass backwards in order to take up the wear, as the bearing becomes enlarged owing to the constant revolution of the crank pin within it. The back projection (L) on the top of the strap is a lubricator, which in the case of almost all connecting rods is forged solid with the strap. If the lubricator were a separate piece screwed in, there would be danger of it working loose, and being thrown off. The brass is made with side flanges (F) so that it cannot shift laterally.

The *driving axle* is shown at 80 (Fig. 1) this being a section through the middle, on which portion the eccentric sheaves (70) are fixed. The crank pin (67) is also shown in section and is usally in one piece with the axle, the connection between them being formed by the crank webs (68).

CHAPTER IV

VALVES AND VALVE GEAR

Slide Valves.

In the plate Fig. 1, an examination of the cylinder of the engine will show that there are three passages opening out on to the planed surface on which the valve works. The left-hand opening or port communicates with the cylinder in front of the piston, and the right-hand port with the other end of the cylinder at the back of the piston. There is, in addition, a third central opening beneath the middle of the valve, which communicates with the exhaust passage leading to the blast pipes.

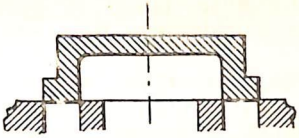


Fig. 8.—Original Form of Slide Valve without Lap.

If the valve (Fig. 10, D) moves some distance to the left, the right-hand port is opened for the admission of steam to the back of the cylinder, and the left-hand port will be placed in communication with the central exhaust port, through which the steam in the front of the cylinder escapes to the blast pipe and chimney.

The original form of slide valve is shown in Fig. 8 for the purpose of explaining what follows. It will be observed that this valve, when in its central position, just covers the two steam ports. Moreover, when the valve is in this position, the piston is at one end of its stroke, and the eccentric* is then at right angles

* It may be noted that the eccentric is in reality equivalent to a crank with a short "throw" or radius.

to the crank. Such a valve, placed exactly in the central position when the piston is at the extreme end of its stroke, has certain vital defects in working. It does not allow of the expansion of the steam in the cylinder, and therefore involves enormous waste. For if we imagine the valve being moved to the right-hand, the left-hand port is open to admit steam until the valve has travelled as far as it can to the right and returned to its original central position, as in Fig. 8. This requires exactly half a revolution of both the eccentric and the crank, and during half a revolution of the crank the piston travels from one end of its stroke to the other. *i.e.*, the steam enters the left-hand port during the whole stroke and there is no expansion at all. The working steam in the cylinder is at practically the full boiler pressure until the exhaust port is opened, whereupon the steam passes to waste instead of being first expanded down to nearly atmospheric pressure.

Again, the steam cannot escape from the right-hand port to the exhaust until the left-hand port has opened to admit steam at the other end. The process of exhausting takes an appreciable time, hence the exhaust steam has to be forced out to some extent by the piston, and this causes a resistance or back pressure against the pistons. The fact that the valve admits steam exactly when the piston is at the end of its stroke has the disadvantage that there is no cushioning effect, and the running engine is carried over its dead-centres by the inertia of the moving parts, hence harmful knocking is produced in the connecting rod bearings at each reversal of the piston.

Lap and Lead.

Two modifications must be introduced to produce a workable engine. To obtain expansion by cutting off the steam before the end of the stroke, the ends of

the valve are extended at the edges which cover the ports. This extension is termed the *outside lap*, and is shown at L in Fig. 9. It is now obvious that when the piston is at the front end of the stroke and ready to receive steam through the left-hand or front port, the valve must be moved towards the back through a distance (L) before the port can open, and steam be admitted. This means that we must also shift the eccentric round the axle towards the back through an angle which will just move the valve through a distance equal to the outside lap of the valve. The centre of the eccentric is then no longer at 90° to the crank, but is placed at an angle in

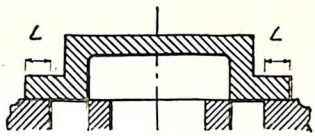


FIG. 9.—SLIDE VALVE WITH OUTSIDE LAP.

advance of 90°. The edge of the valve can, however, only begin to uncover the steam port when the piston is at the extreme end of the stroke. At this point the piston ought to be receiving steam, but the valve is still just closing the port. To get over this, the eccentric is moved round the axle a little further, so as to increase slightly the angle through which it is advanced. This pulls the valve somewhat further to the right, when considering the left-hand or front port, so that this port is slightly open when the piston is at the end of the stroke. This is termed the *lead* of the valve. The total angle through which the eccentric has had to be moved from its original position at 90° with the crank to give the necessary lap plus lead is termed the *angle of advance*. It should also be noted that the effect of lead is to

open the port to steam a little before the piston has reached the end of its stroke. Steam so admitted acts as a cushion in preventing the injurious knocking mentioned above.

The Operation of the Slide Valve.

To understand the operation of the slide valve it is necessary to follow the motion through a complete revolution, whilst the piston is making two strokes, one in each direction. In the diagram, Fig. 10, the left-hand side is the front of the cylinder, and the right-hand side the back. The latter is the nearest to the crank of the engine.

In Fig. 10 (A) the piston is at the front end of the stroke, and the front port is slightly open by the amount of the lead, so that steam is being admitted to the front of the piston. Both valve and piston are moving towards the back. The back port is open to exhaust, and the steam at the back of the piston is being discharged to the blast pipe underneath the middle of the valve and through the central port.

In Fig. 10 (B) the valve is at the extreme back end of its stroke, the front port is fully open with the piston in the position shown and moving towards the back. The back port is now fully open to exhaust.

In Fig. 10 (C) the direction in which the valve was moving has reversed, and it is now moving towards the front. In the position shown the front edge of the lap of the valve has just closed the front port, and this is the point at which the steam for the front of the piston is cut off. The piston, however, has not reached the end of its stroke, and is still moving towards the back. The back port is still open to exhaust, but is being gradually closed as the valve moves towards the front.

In Fig. 10 (D) the piston is still moving to the back, and the steam, which has entered into and fills

the cylinder at the front of the piston, is now shut in and is expanding. In the position shown the back port has just been closed by the *inside* edge

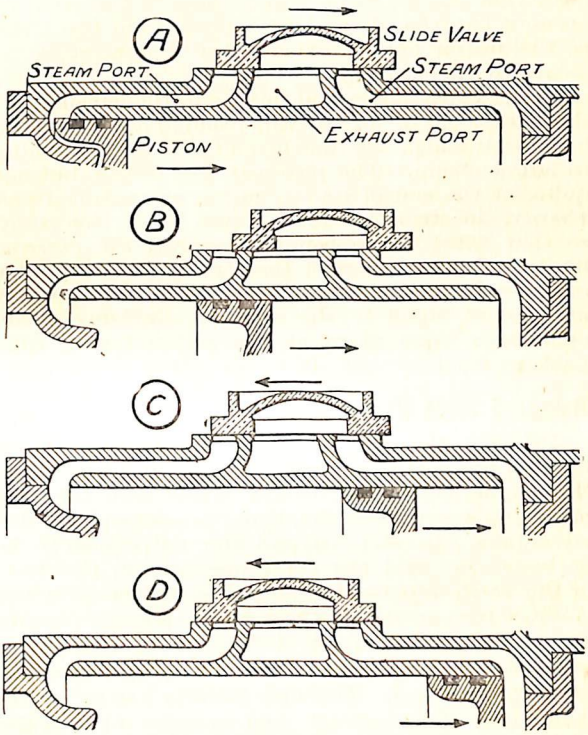


FIG. 10.—SLIDE VALVE MOVEMENTS.

of the valve, and the connection between it and the exhaust is now severed. There is a certain amount of steam imprisoned at the back of the piston, and as the latter completes its stroke this imprisoned

steam is compressed. In this position the *inner* front edge of the valve is just about to open the front port to form a communication with the central port, that is, the front port is just on the point of opening to exhaust, and the steam from the front of the piston having expanded will now begin to escape to the blast pipe.

As the valve moves still further to the left or front the back edge of its lap will reach the edge of the back port, which will now be on the point of opening to admit steam. The piston is now nearly, but not quite, at the end of its stroke for, as explained previously, the steam is admitted just before this point, so that when the piston has reached the extreme limit at the back end of the stroke, the back edge of the valve is slightly uncovering the back port by an amount equal to the lead. A similar cycle of operations takes place as the piston moves from back to front.

Balanced Slide Valves.

Although the slide valve of the form described is fitted to by far the greater number of locomotives throughout the world, it has, when used for very large engines with high steam pressures, one disadvantage. In such engines the valve has to be of large size, and the total pressure on the back of the valve, forcing it against the surface on which it slides, is so great that the resulting friction requires an undue proportion of the power of the engine to overcome. To remedy this two modified forms of valve are used. The first form is known as the "balanced slide valve," and consists of a valve of the ordinary form, which slides between the machined surface on to which the ports open, and a planed plate fixed to the cover of the steam chest. This plate bears upon the back of the valve, and prevents the steam from acting upon the latter. Four strips of steel in the form of an "Oxford

frame" are let into grooves in the back of the valve, and springs beneath them force the strips against the plate to make the area enclosed in the frame steam-tight. This excellent valve is of American origin and is used when the valves are on the top of the cylinders, but it is not applicable to the common form of steam chest between the cylinders.

Piston Valves.

The second form is the "piston valve," which originated in this country, and is now used all over the world, more especially on engines using superheated steam. Two circular liners (Fig. 11) are fixed in the steam chest, forming cylinders inside which work two pistons. These pistons are perfectly balanced, since the steam cannot press them on to the port faces, but can act only upon their ends in the plane in which the valve is moving. As the pressure on the ends is equal, little force is required to move the valve beyond that necessary to overcome ordinary friction. The two pistons are connected by a spindle, so that both move together as one valve, and their action in respect to opening and closing the steam and exhaust ports is similar to that of an ordinary slide valve. Their construction is, however, much more complicated, because means have to be provided to give an emergency exit for water trapped in the cylinder. An ordinary slide valve has the great advantage that should water more than fill the clearance space, the valve will lift slightly from the face over which it moves, and allow the water to escape through the ports. The original piston valves, which were tried nearly 50 years ago, consisted of two solid pistons fitting closely into cylindrical passages, with no provision for the escape of the water. This resulted in a large number of mishaps, and cylinder covers were knocked out. In 1888, Mr. W. M. Smith,

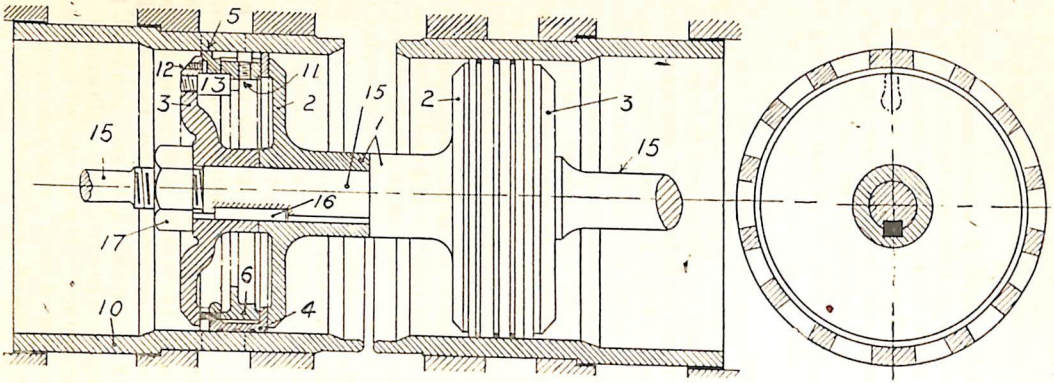


FIG. 11.—ROBINSON'S PISTON VALVE.

of the North Eastern Railway, invented a workable piston valve, in which the pistons are provided with collapsible rings. These are kept up against the cylindrical liner, in which the pistons move, by means of light springs, so that they are tight under normal working conditions, but the springs can give so that the rings collapse inwards under the pressure of any water which is trying to escape.

The piston valve (Fig. 11) is a modification of the same principle, and shows the type designed by Mr. J. G. Robinson, M.Inst.C.E., (Chief Mechanical Engineer of the Great Central Railway), for superheated engines, and used by The Superheater Corporation, Ltd. There are two pistons, one for each steam port, united by the valve stem 15. Each piston is formed of two discs, 2 and 3, between which are situated cast iron packing rings 4, 5, and 6. The liner 10 is pressed into the cylinder casting and is renewable.

The valve shown is for *inside admission*, that is, the steam is admitted to the valve chamber between the pistons by the top central port. The two ports at the bottom communicate with the front and back of the piston respectively. Through each of these the steam is admitted to and exhausted from the cylinder. The two top outside ports are those through which the exhaust escapes from the valve chamber to the chimney. If the pistons move to the right, steam will be admitted to the right-hand bottom port, and exhausted from the left-hand bottom port. This arrangement (which is the reverse of that of the slide valve, which always has *outside admission*) has the advantage of keeping high pressure, superheated steam away from the glands, through which the valve spindle passes, and thus reduces leakage of steam through them. Only low pressure exhaust steam comes into contact with the glands.

Valve Gears. Stephenson's Link Motion.

There are several different forms of valve gear, the principal forms being: (1) Stephenson's shifting link motion, (2) Gooch's stationary link motion, (3) Allan's straight link motion, (4) Joy's radial valve gear, and (5) the Walschaerts valve gear.

The Stephenson link motion, as shown in Fig. 1, is the most usual form. It is, however, being gradually supplanted, more especially in outside cylinder engines, by the Walschaerts gear. The Allan and Joy gears are to be found on a large number of British locomotives, but the Gooch link motion is practically extinct.

In the Stephenson motion, two eccentrics are used for each cylinder. The sheave or central portion of one eccentric is shown at 70 (Fig. 1), together with the eccentric strap (71) inside which the sheave revolves. It will be observed that the sheave (70) is not central with the axle (80) on which it is keyed, and as it revolves inside 71, the eccentric rod (73)—to which 71 is attached—has a to-and-fro movement imparted to it. The other eccentric rod (72) is similarly moved by the other eccentric. The piece 74 is known as the *expansion link*. The fore-gear eccentric rod (72) is attached to the top of the link, and the back gear eccentric rod (73) to the bottom, these attachments being made by means of turned pins. The link (74) is curved, and a long curved slot is machined in it, the concave side facing the crank axle. The valve spindle (28) terminates in a machined block, which fits into the curved slot of the link. In the middle of the expansion link there is a pin to which the straight lifting link (75) is attached. At 76 there is shown in cross section a strong shaft called the reversing shaft, which is carried in the brackets (79), and extends right across the engine and can be rotated through an angle. The brackets (79) are fixed to the frames on either side. The reversing shaft has arms forged solid with it, which, in effect, form a bell-crank lever.

The arms pointing in a nearly horizontal direction from the shaft (76) are connected by means of pin joints to the upper ends of the lifting links (75), whilst another arm (77), pointing upwards, is connected by a similar joint to the long reversing rod (144), the latter terminating on the driver's platform in a connection with the reversing lever (143), the top of which is provided with a trigger. The trigger works a rod the bottom end of which engages in notches cut in the curved quadrant (145).

When the motion is in the position shown in Fig. 1, the block at the back end of the valve spindle is in the middle of the expansion link (74). This portion of the link has very little to-and-fro movement when the engine is running, and the amount of this movement imparted to the valve spindle (28) is not sufficient to enable the valve to uncover the steam ports properly, and therefore hardly any steam is admitted to the cylinders. If the driver moves the reversing lever (143) down to the front end of the notched sector (145), the reversing rod (144) is moved forward. The arm (77) of the reversing shaft (76) is pushed forward, and rotates the shaft through an angle, so that the end of the horizontal arm of the bell-crank lever moves downwards. This action pushes downwards the lifting link (75), and with it the curved link (74). As the eccentric rods (72 and 73) are connected to the curved link (74), these also move downwards with the rest of the system, rotating about a point which may be considered to be the centre of the axle. The final result is, therefore, that the fore-gear eccentric rod (72) is brought into a nearly direct line with the valve spindle (28), and the movement of the latter is such that the valve is practically driven by the rod (72) and the fore-gear eccentric. The valve spindle has so moved the valve that the movement of the engine is chimney first, *i.e.*, the engine is in *fore-gear*.

To reverse the engine and place it in *back-gear* to run tender first, the reversing lever (143) is moved by the driver to the back of the notched sector (145). The resulting movements of all the rods and levers will then be the reverse of those described above, and the eccentric rods will be raised until the back-gear rod (73) is nearly in line with the valve spindle (28).

To enable the driver to pull the reversing lever back more easily, without having to pull up the whole weight of the rods and links, the reversing shaft (76) has a third arm at the back to which a large balance weight (78) is attached. A screw wheel is frequently used in place of the lever (143).

Expansive Working.

The link motion with its reversing gear does more than merely reverse the direction in which the engine moves; it has also the most important function of providing for *expansive working* of the steam in the cylinders. It has been stated above that when the engine is in mid-gear there is not sufficient movement of the valve to open the ports to steam. On the other hand, if the engine is in full fore-gear, and the eccentric rod (72) is in a nearly straight line with the valve spindle, this rod is exerting its full influence over the movement of the valve, and the total distance or "travel," through which the valve moves from front to back is a maximum. If this maximum travel of the valve in full-gear were, say, $4\frac{1}{2}$ ins., it would be about $2\frac{3}{8}$ ins. in mid-gear. Moreover, in full fore-gear the steam is cut-off late, and not until the piston has completed about 75 per cent. of its stroke. The engine is now exerting its greatest starting or pulling power, but at the expense of using a great deal of steam, so much so that if this condition of things continued for long, the engine would run the boiler short of steam, or "out of breath," as the drivers frequently term it.

By means of the notches in the sector (145), the trigger can engage the reversing lever in a considerable number of intermediate notches between the centre or mid-position and the ends. This means that the eccentric rod (72) can be placed in a number of intermediate positions with respect to the valve spindle. The further the distance through which the eccentric rod (72) is lowered, and the nearer it approaches into line with the valve spindle, the greater the travel of the valve and the later the cut-off. When running at speed the engine is *notched up*, so that the travel of the valve and the full amount to which the steam port can be opened are both decreased. Moreover, the point at which the steam is cut off is earlier, and is now, say, at 18 to 22 per cent. of the stroke of the piston, after which point the steam is expanded until released.

Gooch and Allan Link Motions.

The Gooch stationary link motion does not require extended mention. It differs from the Stephenson link motion in that (1) the link is curved with the concave side towards the cylinders instead of towards the axle, and (2) the link is stationary, the block attached to the valve rod being moved up and down inside the stationary link. This valve gear, invented by Sir Daniel Gooch, was always used on the broad (7 ft.) gauge engines of the Great Western Railway, and on the engines of several other English railways but it is now obsolete in this country. It found great favour in France, where a large number of engines fitted with it are still at work. It has the disadvantage that the drive between the eccentric rod and the valve is not so nearly in a straight line as in the Stephenson gear.

The straight link motion, invented by Mr. Alexander Allan, may be said to be a combination of the Stephenson and the Gooch link motions. It is rarely used

now in new engines, but many engines on the London and North Western Railway are fitted with it. In the Stephenson link motion, the link is concave towards the axle and is movable with respect to the die block on the valve spindle, whereas in the Gooch motion the link is concave towards the cylinders, but is stationary, whilst the die block within it is the movable portion. In the Allan motion, the link is straight without any curvature, and both link and die block move together but in opposite directions,

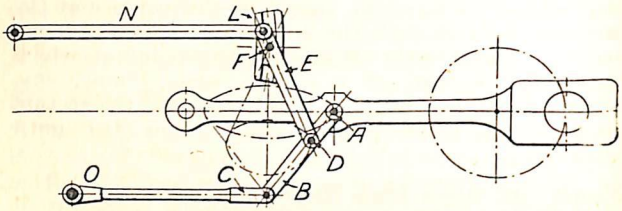


FIG. 12.—JOY'S VALVE GEAR.

the link moving upwards whilst the block moves downwards and *vice versa*. One movement balances the other and no balance weight is required.

Joy's Valve Gear.

The valve gear invented by David Joy, in 1879, is used principally by the London and North Western and Lancashire and Yorkshire railways, on which lines it is standard for nearly all modern engines. It is illustrated in Fig. 12, and is quite different from the valve gears previously described. It belongs to the type known as *radial* valve gears. The movement of the valve is derived from the connecting rod and no eccentrics are required. The point A of the connecting rod is the origin of the movement, and to this the link B is attached.

At its other end, the link B is jointed to the anchor link C, which has a fixed fulcrum at O, where it is pinned to the engine frame. The fulcrum O is the only fixed point in the whole mechanism, the other end of C, to which B is attached, forming a movable fulcrum about which B vibrates. The point A in the connecting rod, and with it the upper end of B, describes the dotted ellipse shown during one revolution of the engine. Another lever (E), termed the valve lever, is jointed to the connecting lever B at a point D, about one-third of the length of B from the upper end. The point D then describes the second dotted curve, which has a shorter length than, but is of the same height as, the ellipse described by A. The valve lever E has a fulcrum at F, about which it imparts motion to the radius link or valve spindle-link N, which at the left-hand end is jointed to the valve spindle. The fulcrum F is attached to a sliding block which is fitted into, and can move freely up and down, the curved quadrant L, the latter being made with a slotted channel inside which the block moves. The quadrant L is pivoted on a transverse shaft carried by brackets fixed to the frames, and can be rotated when required about the centre of the shaft through an angle to alter its obliquity. This movement and consequent alteration of obliquity is made by the reversing lever, which is attached to one end of the shaft on which the quadrant L is fixed. The motion of lever E moves the block up and down the slot in L. The block moves with it the end of the radius rod N, and this movement is imparted to the valve. The back end of N describes an ellipse, and the amount of travel of the valve is equal to the lateral component of this motion of N. The greater the amount of the obliquity of the quadrant L, the more inclined the ellipse, and the greater the amount of travel imparted to the valve. In the diagram the engine is shown in mid-gear, with L in its mid position

without obliquity, and the lateral travel of the back end of N, and therefore of the valve, is then equal only to the lap plus the lead on each side of the central position. The quadrant L is curved to a radius equal to the length of N, and the mechanism is so arranged that the fulcrum of L coincides with that (F) of the lever E when the cranks of the engine are at the "dead centres."

One of the advantages of Joy's gear is the absence of eccentrics on the crank axle; this gives much needed space for strengthening the axle by making the crank pins longer and the webs wider.

Walschaerts Valve Gear.

The Walschaerts valve gear was invented, in 1844, by M. Egide Walschaerts, the manager of the locomotive works of the Belgian States Railways. It has been used for many years in various continental countries, but only since about 1907 has it made any progress in this country, where its use is now extending very rapidly.

Only one eccentric, or crank equivalent to an eccentric, is used for each cylinder, instead of the two necessary for other link motions. A crank is used in place of an eccentric in engines with outside cylinders. The movement of the valve is produced by the combination of two separate motions of the valve gear. In Fig. 13 the large circle represents the path of the crank pin, and the small circle inside it that of the eccentric, which in this case is in the form of the crank shown. The crank pin lies on the horizontal line in the illustration, and the point representing the eccentric centre lies on a line at right angles to it. This condition that the eccentric is at 90° to the crank is one of the leading features of this gear, and means that the eccentric has no angular advance as is the case with other link motions. The eccentric rod ER is attached to a projection at the bottom of the link L, which is suspended

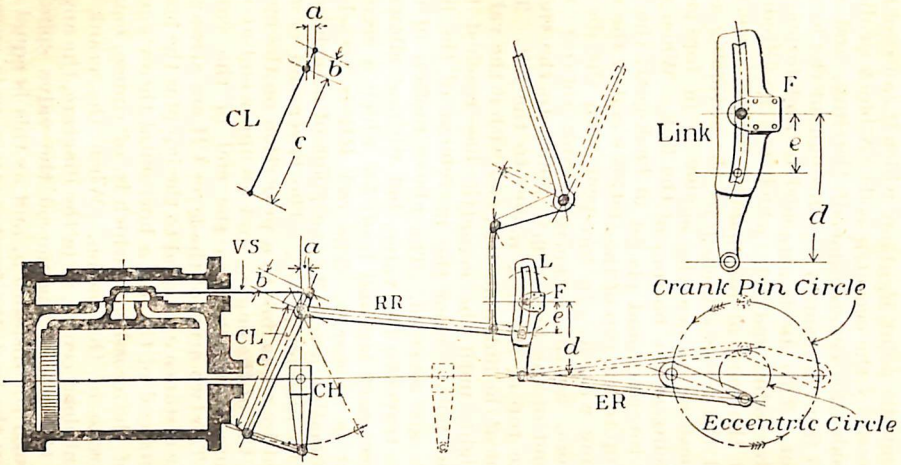


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FIG. 13.—WALSCHAERTS VALVE GEAR.

from its middle point F, about which it can oscillate when moved by the eccentric rod. A block or die is fitted inside the curved slot of the link, and can be moved from bottom to top throughout the length of the slot. This die is attached to and forms the end of the radius rod RR, which can be lifted by means of the vertical rod jointed to RR near the link, and the lever attached to the reversing rod. In the position shown the engine is in fore-gear, the die being at the bottom of the link. When the engine is reversed, and placed in back-gear, the die is pulled up to the top of the slot, the end of the rod RR moving with it. In fore-gear with the die at the bottom, as the eccentric crank rotates the bottom end of the link is first pulled to the right, whilst the top of the link moves to the left. The movement of the link pulls RR, and with it the valve, to the right, until the eccentric has reached the back dead point, when the movement of the link and valve are reversed. The above motion of the gear gives travel to the valve, but without allowing for the necessary lap and lead, for which a second movement is necessary. The rod RR is attached to a combination lever CL, the point of attachment forming the fulcrum of CL. The lower end of CL is attached by a bar link to a projection on the main crosshead CH of the engine, and its upper end above the fulcrum is attached to the end of the valve spindle. The two arms of the lever CH are arranged so that the distance *a* is equal to the lap plus the lead. The bottom end of CL has a horizontal throw equal to that of the crosshead, which is, of course, equal to the stroke of the piston. When the crank is on the front dead centre, as in the diagram, the angle at which CH stands has moved the valve spindle back through the distance *a*, and as this is equal to the lap plus the lead, the front steam port is opened to steam by an amount equal to the lead.

When the die block attached to RR is at the

centre (F) of the link, the engine is in mid-gear—since this point has no movement, and the eccentric imparts no travel to the valve. The only movement of the valve is then derived from the lever CL and is equal to the short distance *a* on either side of the centre, which opens the steam ports only to the small amount equal to the lead.

CHAPTER V

FRAMING, SPRINGS, AXLES AND WHEELS.

Framing.

THE frames in British locomotives consist of two long plates or slabs of steel 1 in. to 1⅛ ins. thick, one on either side of the engine. One of these long plates of irregular outline is clearly shown in Fig. 1. In American engines the frames are built up of strong steel bars 4 or 5 ins. square, or of rectangular section 5 or 6 ins. by 4 ins. In British engines the recesses through which the axles pass, are known as the horns and are slotted out of the solid plate, but in American engines they are known as pedestals, and are usually forged on to the top bar of the frame.

The two frame plates have to be connected to each other to give them sufficient lateral stiffness and to maintain them at the proper distance apart. At the extreme front of the engine, the buffer-beam 1 (Fig. 1) forms a cross stay, and consists of a steel plate riveted to the ends of the frames by angle iron connections. Immediately behind the buffer-beam the cylinder casting, in the case of inside cylinder engines, forms a strong rigid connection between the frames. In engines with outside cylinders this connection is made by means of a strong steel casting riveted to the frames, and if the engine has a leading bogie this casting is provided with a boss underneath resting on the bogie, and through which the bogie centre pin passes. Between the cylinders and the driving axle the strong cast steel motion plate (60) forms a very efficient cross-stay. Immediately in front of the fire-box there is usually added another cross-stay consisting of a plain wrought iron or steel plate riveted to the frames by angle irons at

each side. In Fig. 1, since there are two pairs of coupled wheels in front of the fire-box, the corresponding stay (194) is placed further forward, immediately behind the crank axle. Finally, the frames are firmly united together behind the fire-box by a box casting (146) known as the drag-box, which forms a receptacle for the draw gear or coupling (147) to the tender.

A reference to Fig. 4, which shows diagrammatically a plan view of a 4–4–0 engine, may make the arrangement of framing more clear. In this FF are the main frame plates, which are bent inwards at the front end, in order to allow sufficient lateral movement of the bogie wheels. The staying arrangements between the frame plates are provided by the buffer-beam B, the cylinders C, the motion plate M, the cross-stay T in front of the fire-box, and the drag-box D.

Hornblocks, Axle-boxes, and Springs.

Firmly bolted to the frames and carefully fitted into the horns are steel castings known as the horn-blocks (94), which have planed rectangular faces, inside which the axle-boxes (99) can slide up and down freely. The bottom jaws of each horn-block are tied together, to prevent any spreading of the horns, by wrought iron or steel recessed bars (100) known as "horn-keeps."

The axle-boxes (99) are heavy rectangular boxes of iron, steel, or gunmetal, provided on each of their outer side surfaces with a wide recess into which fit the faces of the horn-blocks. The flanges produced by planing out this recess serve to keep the axle-boxes from moving laterally more than a very small fraction of an inch. If the axle-boxes are made of steel or wrought iron they are bored or planed inside to receive a portion of gun metal, known as the "brass," which is bored out to the radius of the axle, and rests directly upon the latter.

The brass on the portion so bored out is usually lined with soft white metal alloy, which reduces the friction, in case the lubrication is not perfect, and also serves the purpose of protecting the brass of the axle-box, should overheating occur. In such a case the white metal alloy, (which has a lower melting point than brass) softens, and if the overheating be serious runs out, and in so doing forms a soft protection which prevents the journal of the axle from being badly scored and grooved. The top of the axle-box is hollowed out to form an oil reservoir, and the bottom is closed in by a cast iron or steel axle-box keep, which forms a cellar or lower reservoir for oil. A pad of worsted or cotton waste is placed in this keep and is maintained in contact with the journal of the axle by a light spring. The pad is saturated with oil from the cellar, and thus lubricates the journal from below.

The axle-box keep is maintained in position in the axle-box by one or two long pins which pass through both. When one pin only is provided, as is very usual, it is made stout enough to be used as the connection with the spring. This connection, which is made when the spring is underneath the axle-box, consists of an eyebolt with a long head bored out to take the pin. Its shank projects down through the horn-stay, and is coupled to the spring buckle (101) by the pin shown. In the engine in Fig. 1 the driving wheel springs (85) and the coupled wheel springs (89) are underhung, that is, they are below the axle-boxes.

The connection of the springs to the frame can easily be seen from an examination of Fig. 1. To the frame plate on each side of the centre of the axle are riveted the brackets (87), in the bottom ends of which are oval holes for the spring hangers (86) to pass through. The hangers, which take the form of links with an eye at the top and screwed at the bottom, are pinned to the top ends of the

springs and are secured below the brackets by strong double nuts, sometimes with thick india-rubber washers interposed between the brackets and nuts.

Another arrangement with the spring above the axle-box is shown in Fig. 14. In this J is the journal of the axle, A is the body of the axle-box into which the brass B is fitted, and C is the axle-box "keep" or "cellar." The weight of the boiler and machinery of the engine rests on the main frame F, which is suspended from the spring through the pins O and

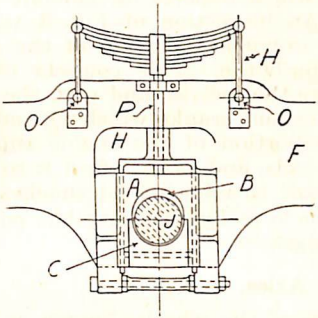


FIG. 14.—AXLE-BOX, HORN-BLOCK, AND SPRING.

the spring hangers H. The load on the spring is transferred through the spring pin P to the top of the axle-box, which has a recess into which P fits. As the axle-box moves up and down in accordance with irregularities of the track, the spring S is deflected.

The springs lessen the shocks received by the wheels when running, and are of several forms, those shown in Figs. 1 and 14 being laminated or plate springs. Spiral or volute springs are very often used, more especially for the driving wheels. The plates of laminated springs are of the best spring steel, about 5 ins. wide by $\frac{1}{2}$ in. thick, the

number of plates varying according to the load to be carried. They are kept together by a band or spring buckle (101), to which the spring pillar or shank of the axle-box eyebolt is fastened.

The greater part of the engine is carried on the springs, or is "spring-borne," as it is termed. This weight is first conveyed through the brackets (87) to the large nuts underneath them; the nuts transfer the load to the spring hangers, so that there is a pull at the top-end pins on each side of the spring, which deflects an amount varying with the load. An inspection of Fig. 1 will show that there is an important portion of the engine which is not spring-borne. This consists of the wheels and the axles themselves, and with the driving axle, the eccentrics and cranks which virtually form part of it. This portion of the engine runs as a dead load on the rails, and as the effect is to subject both axles and rails to undeadened shocks, their weight should be made as light as possible, consistent with proper strength.

Wheels and Axles.

The bodies of the wheels, known as the "wheel centres" are steel castings. Formerly they were of wrought iron, the spokes, rim, and boss being made separately and forged together. Such wheels were very expensive to manufacture and are now obsolete, though many are still at work. The tyres are of hard steel, rolled from a solid hammered ingot, so that no weld is required. They are shrunk on to the wheel centres and then secured either by a fastening ring, or by studs screwed through the rim of the wheel centre and into the tyre.

The axles are of steel, those for all wheels except the driving wheels being known as straight axles to distinguish them from the crank axles of the driving wheels. The driving wheels will, however, also have a straight axle if the engine has outside cylinders,

a crank axle being required only if the cylinders are inside. *Straight axles* have two portions at each end which have to be very carefully turned to exact size in a lathe, viz., the "wheel seats," which are pressed by hydraulic pressure into the wheel centres, and the "journals" which revolve in the bearings of the axle-boxes.

Crank axles are much more complicated forgings, of the form shown in Fig. 15; P shows the crank pins, which take the big ends of the two connecting rods, and W the crank webs, which connect the crank pins to the body of the axle. The webs are flat

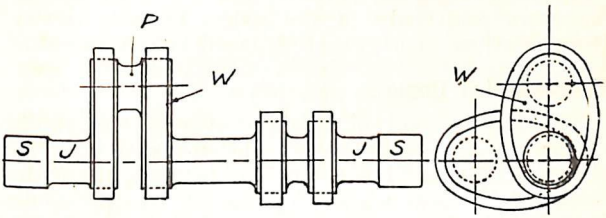


FIG. 15.—CRANK AXLE.

slabs, which may either be rectangular with rounded ends, oval, or circular in shape. A large bolt frequently passes through the crank pin in a longitudinal direction to keep the portions together in case the pin should break, and to strengthen the webs thick wrought iron bands are often shrunk round them, (*see* Fig. 15). The wheel seat is shown at S, and the journals or bearings at J.

Referring to Fig. 1, the end of the web is shown at 65 and a section through the crank pin at 67. The webs and crank pin on one side of the engine are placed at an angle of 90° with those on the other, since when one piston is at the end of its stroke, the other is almost in the middle. In the latter position, the whole force is being exerted in turning the

axle, whereas the other crank is on " dead centre," and cannot exert any turning action until it has moved from that position. If both cranks, instead of being placed at right angles, were placed either on the same side or exactly on opposite sides of the axle, both pistons and cranks would be on dead centre at the same time, and if the engine stopped in this position, it would not be able to start again.

Many modern crank axles, instead of being forged in one solid piece, are built up from separate parts, the webs being shrunk on to the axle and crank pins, and secured with dowel pins. This method eliminates the weak corners where the webs join the pins, and body of the axle. It is generally through these corners that crank axles break.

Four-wheeled Bogies.

The leading end of modern express engines is carried on a separate four-wheeled truck or bogie as shown in Fig. 1. The connection between the main frame of the engine and the bogie is usually made by a pivot and centre pin (54), which form the centre about which the bogie can swivel. The frames of the bogie (43) are quite independent of the main frames of the engine.hT eyare fitted with horn-blocks (49), in which the axle-boxes (48) move up and down just as in the case of the main frames. The two frames of the bogie are bound together by a casting (52), into which the pivot of the engine is recessed. The pivot is attached to a transverse centre casting (55), which is firmly attached to the main frames of the engine. This casting is machined and its bottom surface rests upon the top surface of the bogie casting (52). The pin (54) passes through both in such a way that one can rotate over the other. In addition to the movement of rotation, there is also a second movement which allows of a lateral sliding of the top plate with the pivot over the surface of the bogie casting (52). The total

amount of lateral sliding allowed is from 1 to 1½ ins. in British express engines, but may be made considerably greater for engines which have to run over very severe curves. The lateral movement is controlled by side springs or by a swinging arrangement of links. By removing the pin (54), the body of the engine can be lifted completely off the bogie by means of a crane, and the bogie wheeled out from the front for examination.

The bogie is for the purpose of giving lateral flexibility to the engine, but it serves incidentally to distribute the weight at the leading end of a heavy engine over two axles instead of one. The engine in Fig. 1 has six coupled wheels, which being connected by rods are rigid laterally. If this rigid wheel base were too long the flanges of the extreme wheels would bind between the rails on sharp curves. The remaining wheels are therefore provided with the means for lateral movement, so that they "give" with the curve. Moreover, the action of the side controlling springs, or swing links, is such as to pull the head of the engine round towards the inner side of the curve, and thus guide it on to and round the curve.

Radial Trucks and Axles.

Radiating trucks can, however, be made with one pair of wheels only. In 1857, Mr. Bissell, an American engineer, invented a "truck" or bogie, in which the pivot, instead of being placed between the two axles of a four-wheeled bogie, was fixed behind the bogie, so that the latter radiated as a whole round a centre behind it. The Bissell system for four-wheeled bogies is now obsolete, but is in use all over the world for two-wheeled trucks. The truck is connected to a triangular frame which extends behind it, and the latter has a hole at the apex of the triangle, into which enters a pivot fixed to the main portion of the engine. In modern

engines, the portion of the weight of the engine which rests upon the truck, is usually carried on links which swing laterally from a cross beam attached to the body of the truck. If the pin P, (Fig. 16), is properly placed, the axle of the truck runs radially to the curve, whatever the radius of the latter. This form of two-wheeled truck is frequently known as a "pony truck."

A similar radial motion can be obtained by the use of a radial axle-box of the type invented by Mr. W. B. Adams in this country. The axle-boxes at each end of the so-called radial axle, are arranged with curved instead of rectilinear guides. The

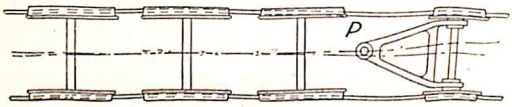


FIG. 16.—DIAGRAM (PLAN) SHOWING BISSELL TRUCK.

centre from which these curved guides are struck is a point which corresponds to the point P of the Bissell truck (Fig. 16), but there is no triangular frame. The axle-boxes simply slide laterally between the curved guides, so that the axle places itself radially to the curve of the line. This type of radial axle, as improved and modified by the late Mr. F. W. Webb, of the London and North Western Railway, is in extended use in this country and the Overseas Dominions, and also on many foreign railways.

Buffers, Draw-gear, and Sanding Gear.

The buffer consists of a cylindrical hollow casting or socket (8, Fig. 1), into which enters the buffer head or plunger (9). The plunger is held in position by a long rod or stem which fits into the hole in the

buffer casting, and as it moves inwards compresses a strong volute spring which takes up the shock.

The leading draw-hook (3) has a stem which passes through the buffer beam, and is secured by a large nut behind the coiled volute spring (4). When the coupling pulls the hook, the spring is compressed. At the trailing end of the engine the connection to the tender is made by a strong draw-bar (147), which has an eye, through which passes the thick pin (185). The arrangement is shown in section in Fig. 1, from which it will be seen that the pin passes through the drag-box casting (146). The pull of the engine is transferred from the drag-box to the pin, and thence to the draw-bar, which is connected to the tender by another thick pin. In addition to the main draw-bar, two somewhat smaller bars are added, one on each side; these are known as safety links and come into action should the main draw-bar or pins break.

The life-guards (7) are attached to the framing at the front end for the purpose of removing stones or other obstructions from the rails. In Fig. 1 they are shown attached to the bogie frame, as is sometimes the case, but it is better practice to fasten them to the main frames, for should a violent blow be given to them, this would be transferred to the bogie pivot. The main frame is much more suitable than the bogie for receiving such shocks.

To prevent slipping of the wheels, fine dry sand is dropped on to the rails when starting or when the rails are greasy. The sand is kept in a cast iron box mounted on the platform or beneath it. This box is shown at 90, and the sand-pipe which conducts the sand from the box to the rails at 91 (Fig. 1). A valve is fitted in the box above the opening into the sand-pipe, and can be opened by the driver by means of a long rod passing into the cab. In modern practice, sand is blown on to the rails by steam or compressed air, and most new British engines are

supplied with steam sanding gear. The sand should be extremely fine and dry, or it will clog in the valve and sand-pipe. Furnaces are provided in all engine sheds for drying the sand.

Brake Gear.

The brake gear may be arranged to work by hand or power, but in all express engines and most goods engines power is used. The power may be obtained from (1) compressed air, as in the Westinghouse brake, (2) atmospheric pressure, as in the automatic vacuum brake, or (3) steam. Very frequently steam brakes are used in connection with the automatic vacuum brake, the former being applied to the engine and tender, and the vacuum brake to the train. The mechanism used to apply the brake blocks to the engine wheels is similar in principle in all cases. A brake cylinder and piston are fixed underneath the foot-plate, and the end of the piston-rod is connected to a bent lever which has one arm attached to a cross shaft, the other arm of the lever being connected to the end of one of the brake rods. In Fig. 1 the latter arm is clearly shown attached to the brake rod (151), the other end (149) of the lever being that connected to the piston-rod of the brake cylinder (148). The brake shaft is supported in bearings at each side of the engine, and can rotate through an angle. The brake rod (151) is connected in front of the wheels to a transverse rectangular beam, which is fastened on both sides of the engine to the brake hangers (195). The brake hangers are suspended at their upper ends from pins which pass through brackets fixed to the frames, so that they can swing about the pins. Near the middle of each hanger is another pin which connects it to the brake block (153).

The action can be seen from an examination of Fig. 1. The lever arms of the brake shaft are so arranged that when air or steam is admitted to the

brake cylinder, the rods (151) are pulled towards the back, and with them the cross brake beams (152). The brake hangers (195) are levers, each having a fulcrum at the top pin, and the pull at their lower end forces the brake blocks (153) against the wheels. As the brake blocks wear away the slack has to be taken up, and it will be seen that the back end of the brake rod 151 (where it is attached to the brake shaft lever 150) is furnished with a number of holes, such that by altering the connecting pin to a hole in front of its present position, the brake rod is pulled back, and the brake blocks (153) are again brought into correct position with regard to the wheels.

CHAPTER VI

COUPLING DRIVING WHEELS, AND BALANCING.

Coupling Rods.

THE coupling of two or more pairs of driving wheels is necessary in order to increase the weight available for adhesion on the rails. Without sufficient *adhesive weight*, the driving wheels do not obtain a sufficient "grip" on the rails to transmit, without slipping, the force exerted at the tread of the wheels, especially when starting with a heavy load. Slipping occurs when the tractive force exerted by the engine exceeds the weight on the driving wheels multiplied by the coefficient of friction between wheels and rails. The weight on one pair of wheels must not exceed about 20 tons in the heaviest engines, owing to the effect on the under bridges and on the rails themselves. On many railways in oversea countries, and on secondary branch lines in this country, the weight may not exceed from 14 to 16 tons per axle, and the engine has to be designed to suit these conditions.

It is not so many years ago that many of the fastest express trains in this country were run by engines having one pair of driving wheels only, without coupling rods. These were very free and fast running engines; the absence of the coupling rods gave less internal resistance to be overcome in the engine itself, and if the adhesion difficulty had not presented itself, express engines would still be constructed with "single" driving wheels.

Amongst the most celebrated of these engines were those with 8 ft. driving wheels (Fig. 17), which worked the Great Northern main line express trains for over thirty years. They were designed by the

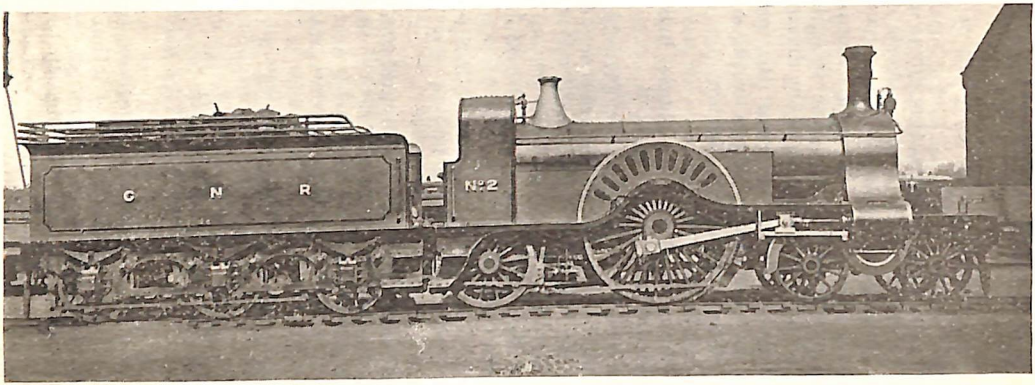


FIG. 17.—GREAT NORTHERN RAILWAY 8-FT. SINGLE EXPRESS ENGINE.

late Mr. Patrick Stirling, and the first of the class appeared in 1870.

In order to obtain quantitative ideas as to the necessity for coupling the driving wheels of a locomotive, a numerical example may be worked. Subject to frictional losses in transmission, the work done on the pistons of the engine is equal to the work done at the circumferences of the driving wheels.

Let p = mean effective pressure (lbs. per sq. in.) of steam on the piston during one stroke,
d = piston diameter, in inches,
l = stroke, in inches,
D = diameter of driving wheels, in inches,
and F = tractive force, in lbs.

Then the total mean effective pressure on the piston = piston area × pressure per sq. in. = $(\pi d^2/4) \times p$; and the work done on the piston during one stroke = mean force on piston × length of stroke = $(\pi d^2/4)\, p \times l$. In a 2-cylinder engine there are two pistons each making two strokes for one revolution of the driving wheels, hence the total work done during this period is $4 \times (\pi d^2/4)\, p\, l = \pi d^2 p\, l$ inch – lbs.

The total work done at the circumference of the driving wheels is the tractive force multiplied by the distance through which this force acts, *i.e.*, the work done = $F \times \pi D$ inch–lbs per revolution of the driving wheels.

Neglecting friction, we have that—

$$\pi d^2 p\, l = F \pi D,$$

whence $F = p\, d^2\, l/D$ lbs.

which is the formula always used to calculate the tractive force.

The adhesion on the rails is the product (weight on driving wheels × coefficient of friction between wheels and rails). The coefficient of friction is greatest when the rails are dry, slightly lower when the rails are very wet but not greasy, and considerably

lower when the rails are greasy. In this country, the coefficient of friction is taken to average $\frac{1}{6}$, hence—

$$\text{Adhesion on rails} = W/6 \text{ lbs.}$$

where W = weight on the driving wheels, in lbs.

By way of example, let us consider an express engine with "single" 7 ft. driving wheels, two cylinders each 18 ins. diameter × 26 ins. stroke, working with a boiler pressure 170 lbs. per sq. in. The weight on the driving wheels is taken to be 18½ tons. When starting a train with late cut-off of the steam, the mean effective pressure on the piston during the stroke may be 0·8 × boiler pressure, *i.e.*, 136 lbs. per sq. in.

Inserting these values in the above simple formulae for tractive force and adhesion, it will be found that the tractive force = 13,640 lbs. and is much greater than the adhesion, which is only 6,907 lbs. In other words, the driving wheels would slip under the conditions assumed. If the train were not a heavy one, the driver would probably be able to start it by giving the engine only a little steam and thus reducing the mean effective pressure during the stroke until the tractive force was made equal to, or less than, the adhesion. The acceleration possible under such conditions is naturally low, and it is in starting that "single" engines are at a grave disadvantage. Under normal running conditions at considerable speed, the cut-off is, of course, relatively early and the tractive force is less than the adhesion, hence no slipping occurs. For instance, in the above example the tractive effort is 6,820 lbs. when working with 68 lbs. per sq. in. mean effective pressure instead of 136 lbs. per sq. in.

In order to improve the starting conditions, we may couple a second pair of wheels to the driving wheels by means of coupling rods. Other factors being as in the example already given, and assuming the weight on the second pair of wheels to be also 18½ tons, we have now a four-wheels coupled engine

with a total adhesive weight of 37 tons, so that the adhesion is now 13,816 lbs., *i.e.*, twice as great as before and greater than the maximum tractive force at starting. The engine is therefore able to start without slipping.

The above is the simplest explanation of the relation between tractive force and adhesion, but in reality the question is much more complicated. The tractive force depends upon the turning moment exerted at each instant, and this varies at every point of the revolution. The steam pressure, owing to the expansion of the steam, varies throughout the stroke of the piston, and this varying pressure is also altered by the effect of the reciprocating masses, *i.e.*, the weights of the pistons, piston rods, and connecting rods, which when moving at high speeds cause inertia forces, and modify considerably the effective pressures.

The turning moment also depends upon the positions of the crank of the engine. When the crank is at right angles to the connecting rod the turning moment is a maximum for that crank, but when the piston is at the end of its stroke, the crank on that side exerts no turning moment at all, and the whole turning moment at that instant has to be derived from the crank on the other side of the engine, which is placed at an angle of 90° with the other.

Again, the weight on the wheels, owing to the effect of part of the balance weights, varies throughout the revolution. When the balance weight is at the top of the driving wheel, there is less weight on that wheel, as the centrifugal force of the balance weight causes an upward force which diminishes the static dead weight on the rail. Conversely, when the balance weight is at the bottom of the wheel, the load on the rail is increased. This branch of the subject is, however, too complex to be considered within the limits of this book.

An example of a locomotive with ten wheels coupled is illustrated in Fig. 18, which shows an engine built by the Midland Railway to the designs of Sir Henry Fowler, K.B.E., the Chief Mechanical Engineer of this company, for banking trains up a severe gradient of 1 in 37. The whole weight of 73 tons 13 cwt. is available for adhesion. There are four cylinders, each 16¾ ins. diameter by 28 in. stroke, and the coupled wheels are 4 ft. 7½ ins. in diameter.

Balancing of Locomotives.

In order to run steadily and without excessive oscillation at high speeds, locomotives must be "balanced." In other words, the internal forces which would cause disturbances must be counterbalanced. The disturbances in question are due to two main internal causes, the revolving and the reciprocating masses of the mechanism of the engine. If a pulley with one side of the rim heavier than the other be fixed on a shaft, and revolved at high speed, the shaft vibrates, owing to the action of the excess centrifugal force on one side. The *revolving masses* in a locomotive, viz., the cranks, coupling rods, and the larger portion of the connecting rod, are so many weights which would throw the system out of balance. Fortunately these revolving masses can be counterbalanced easily and effectively by adding equivalent masses opposite the crank pins or in the rims of the driving wheels, the balance weights being so chosen and so placed that the centrifugal forces upon them are equal and opposite to the resultant forces produced by the revolution of the parts of the engine mentioned.

This, however, is only part of the balancing required. The masses which move to and fro at high speed produce disturbances such as (1) a longitudinal surging, which causes an uneven pull on the coupling between engine and tender, and (2) an elbowing or nosing action which causes the head

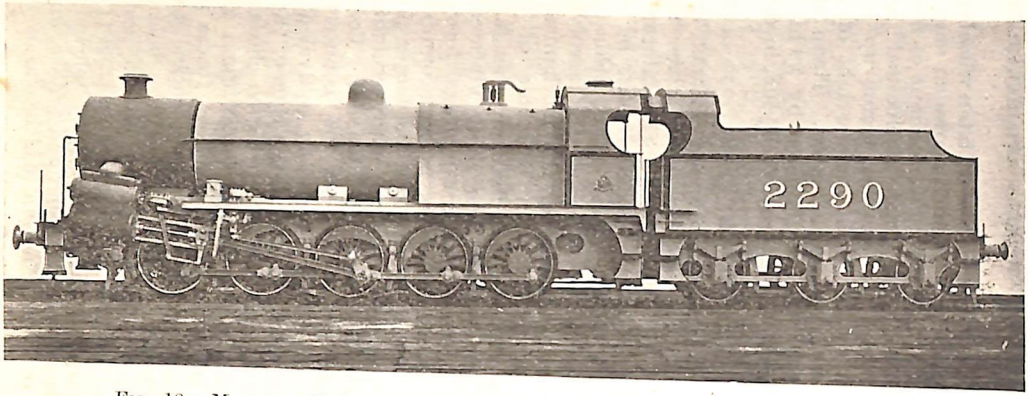


FIG. 18.—MIDLAND RAILWAY 10-WHEELS COUPLED 4-CYLINDER BANKING ENGINE.

of the engine to turn to right and left alternately. The masses which produce these effects are known as the *reciprocating masses*, and consist of the pistons, piston rods, crossheads, and the remaining parts of the connecting rods. They are also balanced by weights in the wheels, but the balance cannot be made perfect. If the whole of the reciprocating masses be balanced, the weights used for this purpose can balance them only in a direction parallel to the centre line of the engine cylinders. The vertical

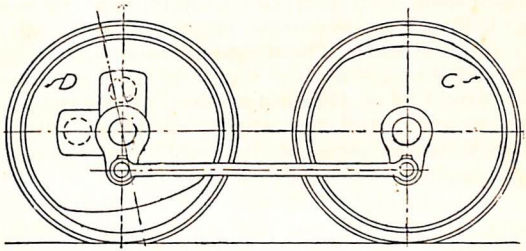


FIG. 19.
DIAGRAM SHOWING POSITION OF BALANCE WEIGHTS.

component of the centrifugal force of these weights does not balance any force. It therefore introduces a new vertical force which tends to lift the driving wheels from the rails when the balance weight is at the top, and to cause excess pressure on the rails when the balance weight is at the bottom. A compromise has therefore to be made, and a portion only of the reciprocating masses (generally two-thirds) is balanced, so that the new vertical force introduced may not be too great.

There are other externally caused disturbances which cannot be balanced. These are due to slight irregularities in the track, the shocks caused by passing over junctions and crossings, and to the

lateral clearance which must be allowed between the tyre flanges and the rails.

The balance weights in modern engines usually take the form of crescents cast solid with the wheels as in Fig. 19. These are hollow and can be filled with molten lead to the extent required. The balance weight of the driving wheel D is larger than that of the coupled wheel C, and is also at a different angle, as it balances part of the reciprocating as well as the revolving masses. The weight for the coupled wheel C balances only the revolving weight of the outside crank, and half the coupling rod in many engines, in which case it is placed opposite to the crank pin and rod. The diagram shows the weights in the left-hand wheels; those in the right-hand wheels would be at different angles. The calculation of the weights, and the angles at which they are set is beyond the scope of this book.

CHAPTER VII

COMPOUND LOCOMOTIVES.

Compounding—General Considerations.

In an ordinary 2-cylinder locomotive, the steam from the boiler passes into both cylinders, and after expanding, is exhausted directly into the atmosphere. In a compound engine, the steam in passing through one cylinder expands only partially, and is then exhausted into another and larger cylinder, in which the expansion is completed. The second cylinder exhausts into the atmosphere. The cylinder into which the steam enters from the boiler is termed the high pressure (H.P.) cylinder, and the second cylinder in which the expansion is completed is known as the low pressure (L.P.) cylinder.

A compound locomotive may have two, three, or four cylinders. If there are only two, one is the H.P. and the other the L.P. cylinder. If three cylinders are employed, there may be one H.P. exhausting into two L.P. cylinders, or two H.P. cylinders and one L.P. cylinder. In a 4-cylinder compound locomotive, there are always two H.P. and two L.P. cylinders.

The L.P. cylinders are larger than the H.P. cylinders, and the efficiency of the engine depends to a great extent upon the ratio of the volumes of the two. In the majority of compound locomotives the stroke of both H.P. and L.P. cylinders is the same, and in such cases the volume ratio of the cylinders is equal to the ratio of the piston areas.

Taking the case of the simplest form of compound engine, with one H.P. and one L.P. cylinder, the latter having double the volume of the former,

and the stroke of the pistons being the same. If the H.P. cylinder has a diameter of 19 ins., its area is 283·5 sq. ins., and the L.P cylinder area is $2 \times 283{\cdot}5 = 567$ sq. ins., corresponding to a diameter of $26\frac{7}{8}$ ins. In practice this would be made 27 ins. diameter. If we assume that the steam is cut off at 50 per cent. of the stroke and expanded, at the end of the stroke the initial volume of the steam will have doubled and become two volumes. These two volumes of steam are now admitted to the larger L.P. cylinder, and if it be supposed that there is no drop of pressure or loss between the two cylinders (which is not the case in actual practice), the steam will now occupy only half the length of the L.P. cylinder, since the area of the latter is double that of the H.P. cylinder. In the L.P. cylinder the steam is again cut off at 50 per cent. of the stroke, and expanded. At the end of the stroke its volume will have again been doubled, and is then four volumes. If instead of compound cylinders we have a simple cylinder 27 ins. diameter, and cut off the steam at 25 per cent. or one quarter of the stroke, the amount of steam admitted before cut off takes place is the same as that previously admitted to the 19 in. cylinder, which cuts off at 50 per cent. or half stroke. The cut-off in the second case being at one-quarter of the stroke, the steam will expand to four volumes during the stroke, *i.e.*, to the same final volume as in the first case. We have therefore attained exactly the same result, and the total expansion is the same as if the 19 in. H.P. cylinder had been suppressed, and the work had been done in the 27 in. L.P. cylinder only. In one respect the latter method would have been more advantageous, in that the loss due to drop of pressure between the H.P. and L.P. cylinders would have been avoided. The same theoretical result would be attained whatever the number of cylinders, provided the ratio of expansion remains unchanged.

Reasons for Compounding.

The question will naturally be asked, why go to the expense and complication of compounding, when the same result can apparently be obtained in a simple cylinder? The reason is that certain serious disadvantages are involved if we attempt to perform the whole of the expansion in one cylinder.

For economical working, the steam should theoretically be cut off so early in the stroke that it is expanded nearly to atmospheric pressure at the end of the stroke, and at high speeds this is done as far as practical considerations permit. If the cut-off be late, the steam is exhausted into the atmosphere at too high a pressure, with consequent waste of energy. The various locomotive valve gears in use do not, however, allow of very early cut-off without incurring grave disadvantages. At high speeds the steam ports, as the travel of the valve decreases, do not open to a sufficient extent to allow the steam to follow up the piston, and the steam pressure falls during admission, causing a loss. This phenomenon is known as *wire drawing*, and is inseparable from a very early cut-off. The point of the piston stroke at which the exhaust opens occurs too soon, and the steam is discharged before it has done its work. A little later during the stroke the exhaust port closes too soon, and traps a certain quantity of steam in the cylinder, which is compressed by the piston. Although compression up to a certain point is necessary and of advantage in a high speed locomotive, excessive compression causes trouble in the form of "knocking" of the connecting rod big ends, and it also represents negative horse power.

Temperature Range.

Another and very important disadvantage of a too early cut-off is the loss caused by the difference between the temperatures of the incoming and

exhausted steam. It must be remembered that fresh hot steam is admitted to the piston through the same port as that through which cool exhaust steam has just left that end of the cylinder. The entering steam is therefore cooled and partially condensed by the cylinder walls. The resulting water of condensation is partially re-evaporated towards the end of the stroke. If steam at 180 lb. gauge pressure be admitted to the cylinder of a simple locomotive, its initial temperature is nearly 380° F., and the final temperature, if it exhausts at 5 lb. above atmospheric pressure, is about 228° F. There is therefore a difference of 152° F. between the entering and exhausting steam. In a compound engine in which the expansion is done in two stages, the steam enters at 380° F. as before, and supposing the cut-off to be 50 per cent., and no losses to occur, the temperature of the exhaust from the H.P. cylinder would be about 326° F., the difference being only 54° F. In the same way the temperature differences in the L.P. cylinder would also be greatly decreased. Less cooling of the steam and consequent diminished loss of heat would result.

Clearance.

The above considerations have taken no account of the "clearance" volume of the cylinders. The *clearance* may be defined as the waste space at each end of the cylinders, and consists of two portions. For obvious practical reasons the piston cannot be allowed to touch the cylinder covers at the ends of its stroke, and it is necessary to allow from $\frac{1}{4}$ to $\frac{3}{8}$ in. between cover and piston at each end of the stroke. To the volume of this space must be added that of the ports between their inlet into the cylinder and the bottom face of the slide valve. At each stroke of the piston the clearance space has to be filled with steam, and if there is very little compression, the amount of work done on the piston

by a unit volume of steam is considerably less than if there were no clearance. On the other hand, if the compression of the steam behind the piston, after the exhaust is closed, be high, the loss from this cause is considerably reduced. Usually, however, there is considerable loss from clearance, especially if the clearance volume be large.

In the case of a compound engine, the fresh steam from the boiler enters the H.P. cylinder, the clearance space in which is smaller than that in the equivalent simple engine with a cylinder equal in size to that of the L.P. cylinder, and the loss is therefore reduced.

It should be added that clearance has another effect in completely altering the ratio of expansion, so that the figures given above, in comparing a simple with a compound engine, do not show the real ratio of expansion. Neglecting the effect of clearance, the apparent ratio of expansion, with cut-off at 25 per cent. of the stroke, was —

$$\frac{\text{Volume of cylinder}}{\text{Volume to point of cut-off}} = \frac{1}{\frac{1}{4}} = 4$$

If, however, the clearance volume be 7 per cent. of the cylinder volume, the real ratio of expansion is—

$$\frac{\text{Volume of cylinder + clearance}}{\text{Volume to point of cut-off + clearance}} = \frac{1+\cdot07}{\frac{1}{4}+\cdot07} = 3\cdot35$$

and the steam is expanded only about $3\frac{1}{3}$ times instead of 4 times. The earlier the cut-off the greater will be the difference between the apparent and the true ratios of expansion.

Cylinder Ratios.

The ratio between the volumes of the H.P. and L.P. cylinders of compound locomotives should not be less than 2 to 1, and may be as great as 3 to 1. Usually the ratio lies between 2·25 and 2·5. There are successful compound engines in Germany and

Austria in which the proportion is from 2·85 to 2·95. On the other hand, the 4-cylinder compound engines of the London and North Western Railway had the low cylinder ratio of 1·64 in one class, and 1·87 in another, but these engines cannot be said to have been very successful, and they are now being converted to simple engines. The excellent 3-cylinder compound engines of the Midland Railway have a cylinder ratio of 2·45.

Advantages and Disadvantages of Compounding.

The following is a *résumé* of the advantages claimed for the compound locomotive compared with the 2-cylinder simple locomotive.

1. More economical use of higher pressures.
2. Less " wire-drawing " of steam at high speeds.
3. Reduced condensation of boiler steam entering the cylinder.
4. Reduced loss due to " clearance."
5. Reduced straining actions on the driving axle and working parts.
6. Less slide valve friction, since the effective pressure on the back of each valve is less than in a simple engine. Reduced valve friction means less wear and tear of the valve gear.

Some of the above advantages, especially No. 5, practically disappear when comparing the compound locomotive with a 4-cylinder simple engine, in which the drive is divided between two axles.

Against the above may be set the following disadvantages—

1. Extra cost of construction, and cost of upkeep, especially in the case of compound engines with three and four cylinders.
2. Large low pressure cylinders are cumbersome, and present more cooling surface than the smaller cylinders of high pressure engines.
3. Compound engines require more oil than 2-cylinder simple engines, but this objection does

not apply when comparing them with 4-cylinder simple engines.

4. Compound engines are not generally adapted for running with both heavy and light trains, for when running with a light load, the early cut-off, dictated by considerations of economy, might result in the steam being expanded to lower than atmospheric pressure and, to avoid this, a later cut-off would be required, involving heavier steam consumption than required by the load itself. The compound engine shows to best advantage with a heavy load at more or less constant speed, and with few stops. These are the conditions under which a marine condensing engine works, but the fact that compound and triple expansion engines have been a great success in marine engineering is absolutely no guide as to its efficiency in locomotives, which work under totally different conditions. Instead of having constant loads and constant speeds, the locomotive is working with continually varying loads and speeds, and over the ever-changing gradients of the railway. Moreover, it frequently has to haul a heavy fast express in one direction, and return with a comparatively light slow train in the other. Compound engines have proved successful in some countries, such as Argentina, where the loads are heavy and the lines are very level ; in fact where the conditions under which the engines work do not vary so greatly. The French 4-cylinder compound engines, mentioned later, are also extremely successful and efficient machines.

Two-Cylinder Compound Locomotives.

The 2-cylinder compound locomotive was originated in 1876, by a French engineer, M. Mallet. It was afterwards taken up in Germany, and later, in 1884, by Mr. T. W. Worsdell on the Great Eastern Railway. The cylinders were arranged as in an ordinary locomotive, and merely entailed the substitution

of a large L.P. cylinder for one of the two cylinders of an ordinary locomotive. Thus Mr. Worsdell, instead of using two 18 in. cylinders, as in his simple engines, employed one 18 in. H.P. cylinder, and one 26 in. L.P. cylinder, and the two cranks were arranged at the usual angle of 90°. The cylinders of these engines were inside, but those of V. Borries' German engines were outside.

The first difficulty to be overcome in the 2-cylinder compound engine was to make the engine such that it could start properly. Only the one H.P. cylinder could receive steam from the boiler, and if the H.P. crank happened to be on "dead centre," starting was impossible. An arrangement had therefore to be devised whereby boiler steam was admitted to the L.P. cylinder by means of a special starting valve, and to avoid the excessive straining action caused by high pressure steam acting upon the large area of the L.P. piston, a spring loaded relief valve was fitted to the L.P. cylinder to limit the pressure to 100 lbs. per sq. in. in that cylinder. In order to prevent high pressure steam from passing through the "receiver" pipe from the L.P. to the H.P. cylinder, where it would oppose the effort of the L.P. piston, an intercepting valve was provided to close the passage from the L.P. to the H.P. cylinder. The engine once started, the exhaust from the H.P. cylinder, on attaining a certain pressure, opened the flap of the intercepting valve and automatically closed the starting valve, so that the engine then worked as a compound engine. Without automatic action the opening and closing of the valves would be left to the driver, who might work the engine uneconomically as a simple engine with one side overloaded.

In a 2-cylinder compound locomotive, a steam reservoir or "receiver" is placed between the H.P. and the L.P. cylinders, and stores the steam exhausted from the H.P. cylinder until the L.P. cylinder

is ready to take it. The receiver usually takes the form of a large pipe placed inside the smoke-box, where it is kept warm by the hot gases, and it should have a capacity of at least twice the volume of the H.P. cylinder. This allows the two cranks to be placed at any angle with each other, although in a 2-cylinder engine 90° is the angle always adopted.

A large number of 2-cylinder compound engines were at one time in use for passenger and goods service. There is, however, a limit to their capacity, which is fixed by the loading gauge for outside cylinders, and by the distance between the frames in the case of inside cylinders. The maximum distance between the frames of a standard 4 ft. 8½ ins. gauge engine is about 4 ft. 1½ ins., and as more and more powerful engines were required, a stage was reached when no room could be found for the large cylinders necessary.

In the case of goods trains, the 2-cylinder compound proved less handy in service than the ordinary engine, owing to the frequent starting required during shunting operations. Also, it sometimes happened that one cylinder developed more power than the other, and this unsymmetrical working produced racking stresses in the framing.

Four-Cylinder Compound Locomotives.

Following the 2-cylinder engine, the 4-cylinder compound was the next to appear, in 1886, on the Northern Railway of France. The experimental engine had certain features in common with Mr. Webb's 3-cylinder engines on the London and North Western Railway, but without some of their disadvantages. The two L.P. cylinders were outside and drove the trailing driving wheels, and the two H.P. cylinders were inside and drove the middle driving wheels. Steam could be admitted to the L.P. cylinders for starting purposes, and as there were two of them, one was always available for starting,

if the other side happened to be on "dead centre." There was therefore less difficulty in starting than in Webb's 3-cylinder compounds. Like the latter, the two pairs of driving wheels had no coupling rods, an omission which resulted in unsatisfactory balancing. Therefore, in 1891, when further 4-cylinder compounds were built, the two pairs of driving wheels were coupled. This type of engine, due to M. de Glehn, has proved extremely successful in working, and is now standard on all the French railways.

In the 1891 and all subsequent engines, the H.P. cylinders were placed outside and the L.P. cylinders inside. This type of engine has several advantages. The cranks of those more recently built are placed so that the inside and outside cranks on the same side of the engine are at 180° with each other, and at 90° with the corresponding cranks on the other side of the engine, and by this means an almost perfectly balanced engine is obtained. Further, in the French system of arranging that the H.P. cylinders drive the second driving axle, and the L.P. cylinders the front driving axle, the total power exerted by the engine is divided between two axles, with the result that the straining actions on each axle are greatly reduced. These features are not necessarily an exclusive property of the compound engine, for they can be, and are, embodied in 4-cylinder, high pressure, non-compound locomotives.

In these engines it has been found advisable, for starting purposes, to provide a direct exhaust for the H.P. cylinders, with admission of steam at reduced pressure to the L.P. cylinders. The four cylinders can be worked non-compound for a time when dealing with heavy loads. Altogether there are four different ways of using the engine—(1) with four separate cylinders for rapid starting, and in very special cases when running; (2) normal compound working; (3) with H.P. cylinders only; and (4) with L.P. cylinders only. The last two methods

of working are used only in case of breakdown to either the H.P. or the L.P. engines. There are two reversing gears, one each for the H.P. and L.P. engines, so that either engine can be "notched up," and the expansion varied separately. The gears are also arranged to be worked together at will. The driver can thus adjust the distribution of steam to suit all requirements. The admission of steam to the large L.P. cylinders is at least from 40 to 50 per cent. of the stroke, and preferably later for high speeds. On some earlier French 4-cylinder compounds the reversing gears are actuated simultaneously, so that the cut-off in both cylinders occurs at the same fixed relative positions of the pistons.

The Great Western Railway possesses three of these engines, which were built in 1902–3, by the Société Alsacienne at Belfort, and have done excellent work. On the Great Northern Railway there are two 4-cylinder compound express engines on similar principles, which were built at Doncaster.

Another type of 4-cylinder compound locomotive has all the cylinders in a transverse line at the front, and all drive the same axle. In this case, although the "motion" is subject to the lessened straining actions, the driving axle has to take the whole load. Engines of this type were built by Mr. Webb for the London and North Western Railway between 1897 and 1903, both for passenger and goods traffic. The valve gears were not independent as in most of the French compounds. There were only two inside valve gears, the outside H.P. valves being actuated from these by horizontal rocking shafts. This arrangement, though good for, and generally used in, 4-cylinder high pressure engines, does not afford sufficient control over the expansion in compound engines.

Passing mention may be made of one other type of 4-cylinder engine, the tandem or Woolf type, in which the H.P. and L.P. cylinders are in the

same longitudinal line, and actuate one connecting rod. In the tandem system, the steam exhausts directly from the H.P. to the L.P. cylinder without passing through a receiver. The system is now obsolete.

Three-Cylinder Compound Locomotives.

These were at one time used by the late Mr. F. W. Webb on the London and North Western Railway. There were two outside H.P. cylinders and one inside L.P. cylinder, which drove independent uncoupled driving wheels. They had several disadvantages, and the type is completely obsolete.

There is, however, another type of 3-cylinder compound engine in which one inside H.P. cylinder exhausts into two outside L.P. cylinders. This arrangement was first used in 1887 on an express goods engine, designed by M. Sauvage, for the North of France Railway. The system remained in abeyance for some years until 1898, when it was taken up by Mr. W. M. Smith, of the North Eastern Railway, in this country, and an engine was constructed for that railway. The design was, however, very different from that of the earlier French engine.

The 3-cylinder compound engine of the Smith type presents several advantages. The cylinders are comparatively small, since there are two L.P. cylinders to continue the expansion begun in one H.P. cylinder. In the English engines of this type on the Midland and Great Central railways the H.P. cylinder is 19 ins. diameter, and the two L.P. outside cylinders are 21 ins. diameter. Compared with the large 26 to 30 ins. L.P. cylinders of earlier and much less powerful compound engines in this country, the weights of the reciprocating masses, which cause swaying and surging of the engine at high speeds, are greatly reduced. Further, the arrangement with three cylinders gives a much more even turning moment on the crank axle. The engines can be

arranged with all three cylinders driving one axle, (as in the Midland engines), or the power can be divided by using the inside H.P. cylinder to drive the first coupled axle, and the two outside L.P. cylinders to drive the second coupled axle, (as in the Great Central engines). The outside cranks in both cases are placed at the usual angle of 90° as in a simple engine, and the inside H.P. crank bisects the angle between them, and is placed at 135° from both.

The inside H.P. cylinder is supplied with steam directly from the boiler, and exhausts directly into the L.P. cylinder steam chest without the intervention of any receiver pipe. To enable the engine to start, the steam is not only admitted to the H.P. cylinder, but also to the L.P. cylinders by means of a regulating valve, the steam to the latter being reduced in pressure to avoid excessive strains, and also to prevent slipping. When working compound, the pressure in the L.P. steam chests varies from 40 to 60 lbs. per sq. in., but for starting or working a heavy train up a steep gradient, direct steam can be admitted from the boiler to the L.P. cylinders for as long a period as necessary. The regulating valve is so arranged that when the maximum pressure allowed in the L.P. steam chest is reached, the direct steam from the boiler is automatically cut off. A controlling valve in the cab allows the driver to vary the pressure in the L.P. steam chest. The valve gear used is the Stephenson link motion with two eccentrics for each cylinder, and the reversing gear is arranged so that the H.P. motion can be notched up independently of the L.P. motion, or both can be altered simultaneously.

The engine can be worked as a compound, semi-compound, or simple engine. When working semi-compound, only a certain limited pressure of boiler steam is admitted to the L.P. cylinders. Usually semi-compound working is employed only when

ascending severe gradients with heavy trains, and during normal running compound working is used, since the horse power developed in compound working is equal to that of an ordinary simple engine. In semi-compound working most of the work is done in the L.P. cylinders, a much smaller proportion being left to the H.P. cylinders. In fact, the engine may

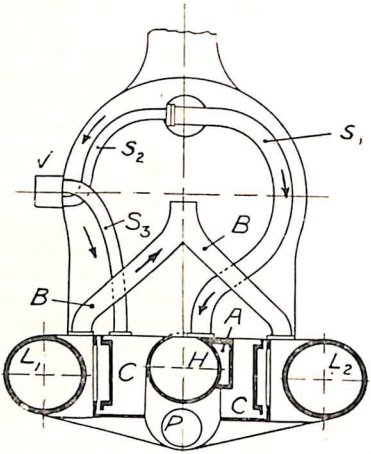


FIG. 20.
THREE-CYLINDER COMPOUND ENGINE (SMITH'S SYSTEM).

be considered to be a simple engine with two large outside cylinders, with the addition of one high pressure cylinder, which can be partly or completely cut out when the load becomes too great for compound working.

The flow of steam in a 3-cylinder Smith compound engine, is shown diagrammatically in Fig. 20. When working compound in normal running, steam from the boiler flows down pipe S_1 into the H.P. steam

chest A, and thence enters the H.P. cylinder H. After doing part of its work in H, the steam is exhausted into the L.P. steam chest CC, thence enters the two L.P. cylinders L_1 and L_2, and finally exhausts up the branches BB of the blast pipe to the chimney. When starting as a non-compound engine, boiler steam also passes through pipe S_2 to valve V, and thence through S_3 to the L.P. steam chest CC, and enters the L.P. cylinders L_1 and L_2, the pressure being reduced to a pre-determined amount by valve V. When the limiting pressure is reached in pipe S_3, the valve V closes automatically, and the engine then works compound. At the moment of starting there is no pressure in pipe S_3, and the boiler pressure in pipe S_2 opens the valve.

In the Midland engines of this type, Mr. R. M. Deeley modified the arrangements by doing away with the reducing valve, and using a double headed regulator. This simplified the engine, but limited the driver's control when running up a heavy bank, as he is unable with these engines to increase the pressure in the L.P. steam chests by introducing a subsidiary supply of high pressure steam into them. The Deeley regulator is arranged so that when starting high pressure, steam is admitted to the L.P. cylinders at a maximum pressure of about 180 lbs., but the H.P. cylinder is nearly balanced and therefore practically cut out. To effect this the regulator is only partly opened, when it uncovers a port leading directly to the L.P. cylinders. When the regulator is fully opened, the port to the L.P. steam chest is closed, and the main ports to the H.P. cylinder are opened, so that the engine works as a compound. When working semi-compound, the regulator admits steam to both H.P. and L.P. steam chests. When climbing a gradient, the compound working of the Midland type of engine is altered to semi-compound working by closing the regulator and then partially re-opening it to the position in

which auxiliary high pressure steam is admitted to the L.P. cylinders.

The 3-cylinder engines on the Smith system, both with the original reducing valve, and with the modified Deeley regulator, are extremely successful engines. On the Midland line they work the heaviest and fastest express trains. These engines, and the 4-cylinder French or De Glehn type of engines, are certainly the most successful compound engines now running.

One more type of compound engine remains to be mentioned, viz., the Mallet articulated type, in which there are two independent groups of wheels. The hind group is driven by two H.P. cylinders, fixed to the main frame of the engine. The leading group of wheels forms a truck or bogie, pivoted to radiate about a pin or articulated joint, placed behind it, and driven by two L.P. cylinders. The steam pipe to the L.P. cylinders has to be provided with a swivelling joint in order to turn through the same angle as the truck. These engines are not used in this country, but they are employed extensively on the Continent, on British Colonial railways, and especially in the United States of America, where they have attained enormous dimensions. They are not used for passenger trains, except for banking up severe gradients, but are confined to very heavy freight service in mountainous districts.

The first engine of this type appeared in 1887, and the earlier engines had two groups of four-coupled wheels. The latest engines have eight or ten-coupled wheels in each group, with the addition of pony trucks at each end of the engine. Those of the Atcheson Topeka and Santa Fé railroad, (U.S.A.), are of the 2–10–10–2 type, with H.P. cylinders 28 ins. by 32 ins., and L.P. cylinders 38 ins. by 32 ins.

The private locomotive building firms of this country have built a considerable number of heavy

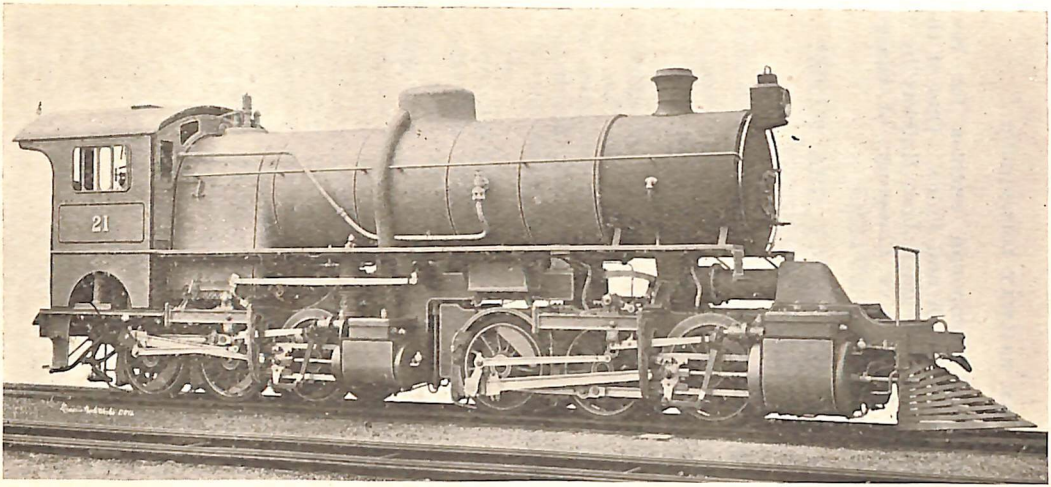


FIG. 21.—MALLET ARTICULATED COMPOUND ENGINE.
By the North British Locomotive Company, Ltd.

Mallet articulated compound engines for South Africa, Uganda, Burmah and China. One of these engines, built for the Pekin-Kalgan Railway by The North British Locomotive Company, of Glasgow, is illustrated in Fig. 21.

CHAPTER VIII

THREE AND FOUR-CYLINDER HIGH PRESSURE ENGINES.

Reasons for Increased Number of Cylinders.

THREE and four-cylinder high pressure engines differ from compound engines only in that compounding is not used. The various arrangements of cylinders are similar, but all the cylinders use high pressure steam, and are generally (though not necessarily) of the same size. Whether three or four cylinders are employed, the power may be divided between two driving axles, or all the cylinders may drive one axle.

Modern locomotives are of such size and power that very large cylinders are required. As the room between the frames is too small for large inside cylinders to be used without valve gear complications, and since the stresses in the crank axle have increased so greatly, the use of outside cylinders has become more general than hitherto in this country. Outside cylinders have the disadvantages that the swaying and rolling of the engine become more pronounced, and the larger balance weights required produce more variation of load on the rails, and therefore more wear and tear on the permanent way. By dividing the power between more than two cylinders, the sizes of the latter are kept within normal limits, better balancing is obtained, and in the case of 3-cylinder engines, there is a more even turning moment on the driving axle. Moreover, as in the case of the French compound engines, the power can be divided between two driving axles, and the straining actions reduced.

Four-Cylinder Engines.

After experimental engines had been tried on two railways, the first really effective engine of this type was designed by Mr. G. J. Churchward, and built in 1906, for the Great Western Railway. Following the system adopted in the French compound engines, the power was divided between two driving axles, each of which was driven by two 14½ in. by 26 in. cylinders. The first engine was of the Atlantic type with the 4–4–2 wheel arrangement, but sixty subsequent engines are of the 4–6–0 type, and there is also one engine of the 4–6–2 or "Pacific" type. In the later 4–6–0 engines the cylinders have been enlarged to 14¾ ins. by 26 ins., and the "Pacific" engine has 15 in. cylinders.

Other railways, such as the Lancashire and Yorkshire, London and South Western, and Great Central, have followed the lead of the Great Western and built engines of this type, with the power divided between two axles.

The 4-cylinder high pressure engines of the London and North Western Railway ("Claughton" class) differ from the preceding in that all the cylinders are in line at the smoke-box end, and the whole of the power is transmitted through the first driving axle. This arrangement throws much more strain on the driving axle, but the arrangement of steam pipes and cylinders is simplified.

The valve gear of a 4-cylinder high pressure engine is simpler than that of a 3-cylinder engine, or than that of a 4-cylinder compound engine. The latter, to work effectively, requires four valve gears, two for each of the high pressure and low pressure engines, so that each of the two sets can, if required, be notched up independently. In a 4-cylinder high pressure engine, the cut-off in each cylinder is the same, and therefore one valve motion serves for the two cylinders on the same side of the engine. The connection between the two valve spindles is usually made

by a pivoted horizontal rocking lever, placed either in front of or behind the inside cylinders.

The cranks of all these engines are set opposite to each other, *i.e.*, at an angle of 180°, on each side of the engine. Thus the right-hand inside crank is at 180° with the right-hand outside crank, but is placed at 90° with the left-hand inside crank. The result is that the two pistons on the same side of the engine are moving in exactly opposite directions at the same instant, and the engine is balanced in so far as the reciprocating masses are concerned. In a high speed engine this is a very important advantage, and only the revolving weights remain to be balanced.

Three-Cylinder Engines.

The first 3-cylinder engine was built by Messrs. R. Stephenson & Co., in 1846, after which the idea lay dormant until the Great Eastern Railway built, for London suburban traffic, a large ten-wheels coupled tank engine, which has since been broken up. The Great Central Railway, in 1907, had constructed for them by Beyer Peacock & Co., Ltd., four heavy 3-cylinder banking engines, each cylinder measuring 18 ins. diameter by 26 ins. stroke.

In 1909, the North Eastern Railway also built ten heavy banking engines, and has since adopted the 3-cylinder system for nearly all classes of engines, including the heavy express engines which work the main line East Coast trains.

In the modern 3-cylinder high pressure engine the cranks are set at equal angles of 120°, and thus a very even turning moment is obtained, but three valve motions are required, one for each cylinder. In this respect the 3-cylinder engine is at a disadvantage in comparison with the 4-cylinder engine which requires only two valve motions, as in an ordinary 2-cylinder engine. On the Great Northern Railway, however, there has recently appeared a

3-cylinder mineral engine of the 2–8–0 type designed by Mr. H. N. Gresley, in which by an ingenious mechanical arrangement, only two sets of valve gear are used to drive the three valves.

In the Great Central engines the power is divided between two driving axles, but in the North Eastern engines, and the new Great Northern mineral locomotive, all three cylinders drive one axle.

The 3-cylinder engine is not balanced naturally as is the 4-cylinder engine, but its balance is more favourable than that of a 2-cylinder engine.

On the other hand, the turning moment on the driving axle of the 3-cylinder engine is much more even than that of either 2 or 4-cylinder engines. The turning moment of the 4-cylinder engine is only slightly more even than that of the 2-cylinder engine, the difference in favour of the former being due to cancellation of the disturbing effect produced by the obliquity of the connecting rods. This, however, applies only to the usual type of 4-cylinder engines with the cranks on the same side at 180°, and at 90° with the cranks on the opposite side. It would be possible to design a 4-cylinder engine with the cranks set differently, in which case the turning moment could be made more even at the expense of the balancing.

CHAPTER IX

SUPERHEATED STEAM LOCOMOTIVES.

Steam Superheat—General Considerations.

In an ordinary locomotive the steam produced in the boiler remains in contact with the water from which it is produced, and is taken to the cylinders without further application of heat. Such steam is known as *saturated steam* and is very unstable, since the least reduction of temperature involves the condensation of a portion of it. Such condensation involves serious loss of heat and hence wastage of fuel, particularly since most of the fuel is expended in providing the latent heat of vaporisation which is surrendered directly the steam condenses to water vapour.

For example, in the case of a locomotive working at 170 lbs. gauge pressure, the number of heat units required to produce steam from 1 lb. of feed water at 62° F. is the sum of two portions; (1) 317 units required to raise the water from 62° F. to the temperature of 375° F. corresponding to the pressure in question; and (2) 849·3 units (latent heat) to convert the water at 375° F. into saturated steam at the same temperature, the total being 1166·3 units. If 1 lb. of this steam be condensed to water vapour, 849·3 units of heat are at once lost.

If, however, this steam be superheated to a temperature of, say, 662° F., no condensation can take place until its temperature has fallen from 662° to 375° F. In other words, there is a temperature range of 287° F. in reserve should the superheated steam come into contact with a body, such as the cylinder walls, cooler than itself. The amount of extra heat which has to be added to superheat the steam to 662° F. is 1 lb. × 287° F. × 0·543 = 155·8

B. Th. U., 0·543 being the specific heat of superheated steam at 662° F., and constant pressure.*

Steam cannot, however, be superheated so long as it remains in the boiler in contact with the water. If heat be added under such circumstances, the only effect is to evaporate more water and increase the pressure in the boiler, the steam still remaining "saturated." If the steam is to be superheated, it must be removed from contact with the water in the boiler before the additional heat is supplied, and then it can be superheated without altering the original pressure of 170 lbs., so long as allowance be made for the resulting increase of its volume. This, in the example chosen, would be from 2·48 cu. ft. to 3·46 cu. ft. per pound of steam.

Although the number of heat units required to superheat the steam is small, compared with the amount of heat required to produce saturated steam at the same pressure, there are difficulties in getting the steam to take up the extra heat. Compared with saturated steam, superheated steam is a bad conductor of heat, and it will not easily take up the additional heat required. For this reason smoke-box superheaters (utilising the heat content of the waste gases on their way to the chimney) produce only a moderate degree of superheat. Steam of this nature generally contains particles of water, which have not been evaporated into the thoroughly dry gas desired, and this admixture detracts considerably from the value of the steam, because the water abstracts heat from the superheated portion of the steam. The metal of the superheater tubes must be at a high temperature on account of the bad conductivity of the steam. The particles of water must be evaporated, and the whole of the steam superheated with sufficient

* The values of the specific heat of superheated steam at constant pressure have not yet been satisfactorily settled. The value usually taken is ·48, but more recent researches show that it varies with the temperature. The value ·543 has been taken from Knoblauch and Jacob's experiments.

rapidity. For this reason the superheater tubes are placed in special flue tubes in the boiler as explained later.

Advantages of Superheated Steam.

The principal advantages of superheating are—

(1) The complete evaporation of the particles of water vapour in the steam as delivered by the boiler and the raising of the temperature of the resulting dry steam gas.

(2) The prevention of condensation in the engine cylinders, and resulting economy of fuel.

(3) Reduction in the weight of steam required.

(4) Increase in the tractive effort of the engine.

(1) The ordinary saturated steam supplied by a locomotive boiler often contains from 5 to 10 per cent. of water vapour. The average may be taken at about 7 per cent.* The heat content of this moisture cannot be utilised in the engine and, if the water is present in large quantities, it endangers the cylinders unless measures are taken to release it.

(2) It has been explained that one of the great advantages of compound engines is the reduction of the initial condensation of the (saturated) steam when it enters the cylinders, and comes into contact with metal which has just been cooled by the exhaust steam. The moment that saturated steam is cooled, part of it condenses, and as much as 20 or 30 per cent. of the saturated steam entering the cylinders of a 2-cylinder non-compound engine may be lost in this way. If, however, the steam is superheated to, say, 600° F. there is a large range of temperature in reserve, and although the steam on entering the cylinder is cooled, it is not cooled to the temperature at which it begins to condense.

Not only does superheated steam commence its work unimpaired by condensation, but also, if the

* Recent experiments have shown, in some cases, a figure as low as 2 per cent.

initial superheat be high enough, the steam remains dry throughout the expansion stroke, whereas (in addition to the initial condensation), saturated steam is subject to further condensation as its pressure and temperature decrease during the expansion.

(3) The same *weight* of steam is capable of doing more work when superheated. For a superheat of 200° F. the increase in the volume of the steam above that of saturated steam, at the same pressure, is about 25 per cent. For the same cut-off in the cylinder, therefore, the weight of steam required is about 20 per cent. less, but the fuel saving from this cause is not so great, because extra heat has been taken from the boiler for the purpose of producing the superheat.

Owing to the increased volume of the steam, larger cylinders are used in superheater engines than in engines using saturated steam.

(4) An increase in tractive power has been proved under actual working conditions, more especially with heavy loads and high speeds. More power can therefore be obtained from an engine without increasing its size. This is an important advantage, since many modern engines in this country have reached the limits imposed by the loading gauge. Again, a heavy train can be hauled by a superheater engine which might otherwise require two non-superheater engines.

Evolution of the Modern Superheater.

Although locomotive superheating is of recent date, as regards practical success, the advantages of superheating have been known for very many years. Richard Trevithick applied the system to locomotives, and in 1828 proposed to heat the steam in small iron tubes as it passed from the boiler to the cylinder. The great practical difficulty has been to lubricate satisfactorily the valves and cylinders of engines employing superheated steam. Saturated steam

is itself a partial lubricant, but as soon as the steam becomes an extremely hot dry gas, the valves seize and cut the cylinder faces, unless suitable lubrication is provided. The oil formerly used was vegetable oil, which decomposed under the influence of superheated steam, and it was not until high-class mineral oils came into use, and the methods of applying the oil to the cylinders and valves were greatly improved that superheating could safely be used. The lubricant is generally forced into the valve chambers and cylinders by a mechanical pump worked from the motion of the engine, though sight feed condensation lubricators are successfully applied on the Great Western and London and South Western railways.

The old hemp piston rod packings were quickly burnt and charred by superheated steam, and modern metallic packings are now used.

Once the difficulties of lubrication and packing had been overcome, inventors again turned their attention to the question, and the credit of making high degree superheating in locomotives a success is due to W. Schmidt, of Cassel, who, after a long series of experiments, produced a practical design for locomotives.

As already explained, waste heat is insufficient to produce the desired superheat, hence, heat has to be extracted from the products of combustion whilst they are at high temperature. This is done by substituting for some of the boiler flue tubes of $1\frac{3}{4}$ ins. to $2\frac{1}{4}$ ins. outside diameter, a smaller number of larger tubes from $4\frac{3}{4}$ ins. to $5\frac{1}{4}$ ins. outside diameter. Inside these are placed the superheater tubes. These latter are known as the "elements," and each consists of a tube of $1\frac{1}{4}$ ins. to $1\frac{1}{2}$ ins. outside diameter, bent to form two, or generally four, parallel tubes. The steam to be superheated flows inside these tubes, and receives its heat from the hot gases flowing outside them through the large flue tubes.

The small tubes extend backwards from the smoke-box towards the fire-box for about two-thirds of the length of the boiler barrel.

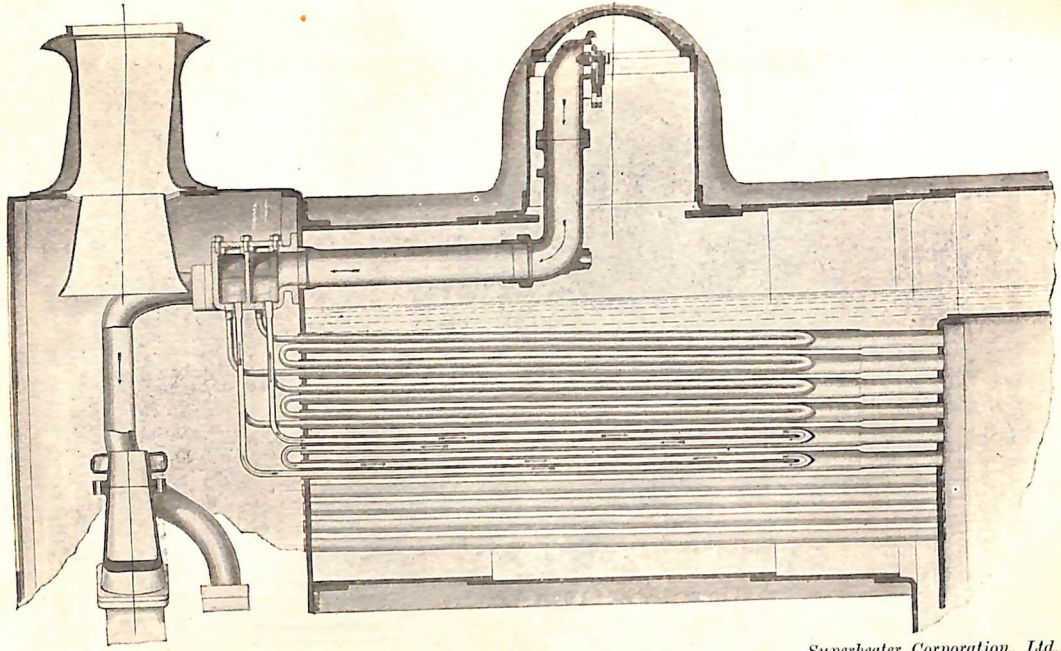
Types of Superheaters.

There are many "smoke-tube superheaters" in use, which differ more or less in the details of their arrangement, but all of them operate upon the principle mentioned above. It will therefore be sufficient to describe the Robinson superheater, which differs from the Schmidt design chiefly in the method of securing the small tubes or elements into the superheater header, and also in the means by which the elements are protected from being burnt, when steam is not passing through them. In the Schmidt system, dampers are used to stop the draught and prevent flames from being pulled through the superheater smoke-tubes, when the engine is not running. In the Robinson superheater no dampers are employed, but in place of them counter steam jets were used as draught retarders, in the earlier designs, and in the latest designs provision is made for circulating steam through the elements in combination with a discharge valve connected with the superheater header.

There are several superheaters in use in this country, other than the Schmidt and the Robinson designs. The Swindon superheater of the Great Western Railway, and the patterns in use on the London and South Western, and Lancashire and Yorkshire railways differ in the arrangement of the superheater elements and headers, but the principle is the same in all cases.

The Robinson Superheater.

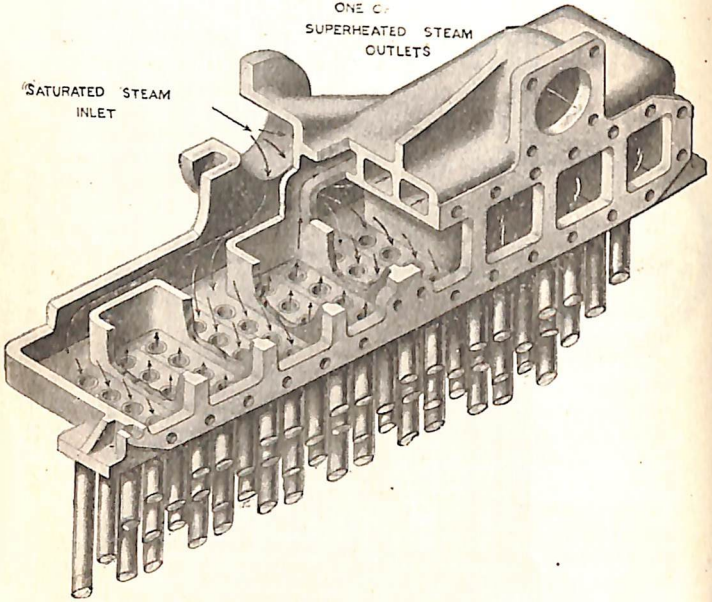
In the Robinson superheater the top rows of small flue tubes in the boiler are replaced by three or four rows of large tubes, inside each of which a superheater steam pipe or element is inserted as shown in Fig. 22.



Superheater Corporation, Ltd.

FIG. 22.—ROBINSON SUPERHEATER.
By J. G. Robinson, M.Inst.C.E., Great Central Railway.

Each element consists of two sets of pipes bent in the form of a U, and connected in the smoke box to a cast steel or cast iron box of special construction, called the "header" (Fig. 23). The header is



[*Superheater Corporation, Ltd.*

FIG. 23.—HEADER FOR ROBINSON'S SUPERHEATER.

divided into two sets of compartments, into the first of which enters saturated steam from the boiler. In a non-superheated engine the steam would be taken straight to the cylinders without the intervention of the header. The header intercepts it, and the saturated steam compartments are provided with outlets through which the steam passes into

the small superheating pipes or elements. Through these it flows up and down the folds of the elements in the large flue tubes, and in so doing absorbs heat from the hot flame and gases which play upon the exterior of the elements. Usually the steam makes a double journey both ways through the elements, and is then conducted back to the distributing side of the header. In flowing through the circuitous course provided by the elements, the original saturated steam becomes thoroughly dried and superheated to a very high temperature. The second set of compartments in the header therefore, contain only superheated steam, which is conveyed thence to the cylinders.

The arrangement is shown in Fig. 23. The superheater elements are secured by expanding them into holes in the header, in the same way as the boiler flue tubes are secured into the tube-plates. This arrangement dispenses with all bolts and nuts. Being held at one end only, the pipes are free to expand and contract without straining the joints. They can easily be extracted by means of a tool designed specially for the purpose.

Preventing Burning of Superheaters.

As long as steam is passing through the superheater elements they will not be burnt by the flame in the flue tubes, but, just as a kettle is burnt if it contains no water, so the tubes of a superheater are burnt if they be exposed to the fierce heat in the flue tubes, without steam passing through them.

In the original designs for the installation of the Robinson superheater, a draught retarder was provided. This consisted of a number of small steam nozzles in the smoke-box, one nozzle extending a short distance into the smoke-box end of each large superheater flue or smoke-tube. The nozzles were connected to the pipe which supplied steam to the blower, so that when the latter was turned

on, the steam to the engine cylinders being shut off, the jet of steam delivered from each nozzle was sufficient to neutralize the forward draught induced by the blower. The flame and hot gases were therefore damped back in the large tubes, so that they could not overheat the small superheater elements.

The most recent improvement to effect the same end, is to provide a means of circulating steam through the elements when the main steam to the engine is shut off. This circulator provides, when the engine is running down-hill without steam, for a small amount of saturated steam to pass from the boiler to the distributing side of the header, circulate through the elements, and finally discharge through the blast pipe without passing through the cylinders. For this purpose, the usual blower valve is replaced by a combined circulating and blower valve, which is placed on the back of the fire-box under the driver's control. The handle is arranged so that when moved to the left, the blower only is operated, but when the handle is moved to the right of its central position, both the blower and the steam circulator are in operation. In the central position of the handle, the blower and circulator are closed.

Large locomotives fitted with steam superheaters are liable to accumulate water in the elements, and from this water there is a possibility of sufficient steam being generated, after the regulator has been closed, to bring about an unintentional movement of the engine. To prevent this, a header release or discharge valve is provided on the side of the smoke-box. This valve is in communication on one side with the cylinder steam chest, and on the other side with the chimney through the blast pipe. It is mechanically operated in conjunction with the regulator handle, so that immediately the regulator is closed the discharge valve is opened, and vice versa when the regulator is opened, the discharge valve is immediately closed.

CHAPTER X

TANK ENGINES AND TENDERS

Tank Engines.

TANK engines carry the requisite supplies of coal and water on their own frames, and therefore are not provided with separate tenders. They are usually intended for short runs and local suburban traffic, for which limited supplies of water and fuel are sufficient. Nevertheless, a certain amount of main line fast traffic, up to distances of 50 to 60 miles, is worked by heavy tank engines. A fine example of an express tank engine is illustrated in Fig. 24.

Generally the tanks are placed on the platform of the engine on each side of the boiler, and the coal bunker behind the foot-plate, where it is accessible for the fireman. The water capacity is often increased by adding a third tank behind, which forms part of the coal bunker. It is necessary that all the tanks should be connected by pipes, so that the water remains at the same level in each. If the water were drawn from one of the side tanks only, before drawing from that on the other side, the weight on one side of the engine would soon become much less than that on the other, and the stability of the engine, due to unequal lateral loading, would be seriously endangered. The connection is made by a large pipe, connected to the bottom of each tank and passing underneath the engine.

The tanks are fitted with transverse partitions which, of course, must not extend to the bottom, or some portions of the water space would be cut off from the others. These partitions serve two purposes, of which the most important is to prevent the heavy "back-wash" of the water when the speed of the engine is suddenly checked. Secondly,

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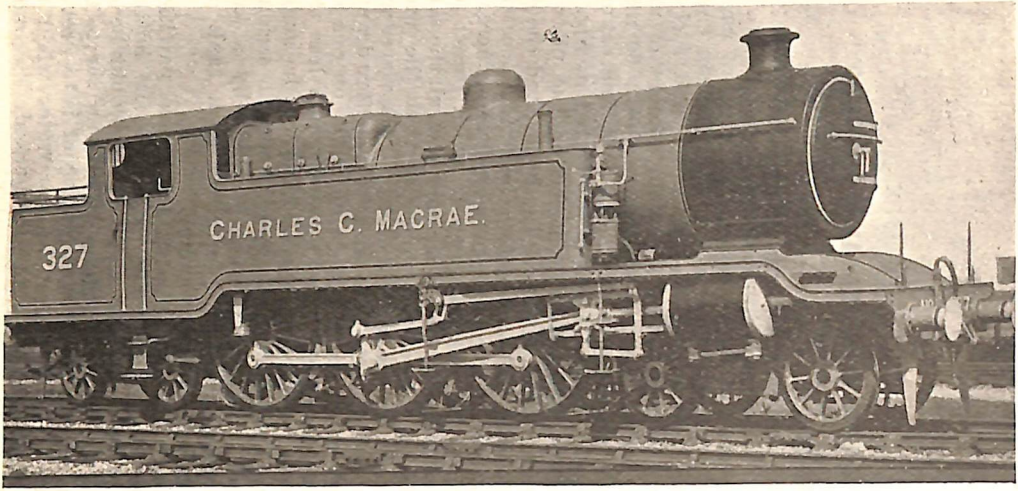

FIG. 24.—LONDON, BRIGHTON, AND SOUTH COAST RAILWAY EXPRESS TANK ENGINE.
4–6–4 type. Coupled wheels 6 ft. 9 in. Cylinders 22 in. by 28 in.

being riveted to both sides of the tank, they act as strengthening stays.

In some engines, principally used for shunting duties and local goods traffic, the tank is placed astride the boiler. Such engines are termed "saddle tanks," but are rarely used for passenger traffic, as they are too top-heavy for high speeds.

The quantity of water carried by a tank engine varies from 800 gallons in a small engine, to 2,000 gallons in large main line tank engines. The majority of local suburban tank engines carry from 1,000 to 1,400 gallons, and about 2 tons of coal. As their journeys are short, they can replenish their supplies at convenient stations, though they should be so designed that they can carry enough coal for a day's work.

Tenders.

A tender is a separate vehicle, designed for carrying conveniently the necessary fuel and water.

A tender engine will carry from 2,000 to 5,000 gallons of water, and 5 to 7 tons of coal. The tender usually runs on six wheels, but for long runs on certain railways, tenders running on two four-wheeled bogies are used. Such large heavy tenders have the grave disadvantage that their weight is a non-paying one, and reduces appreciably the useful load which can be drawn by the engine. To avoid the use of such heavy tenders, a special water pick-up apparatus is frequently used, so that water can be taken up from a trough between the rails, when the engine is running at a high speed.

The framing of the tender (Fig. 25) generally consists of four longitudinal plates, each about $\frac{3}{8}$ in. thick. Two of the plates are on each side, and arranged so that the wheels run between them. The outer frames F only are fitted with axle-boxes. The two inner frames are usually stayed together transversely by plates riveted to them with angle

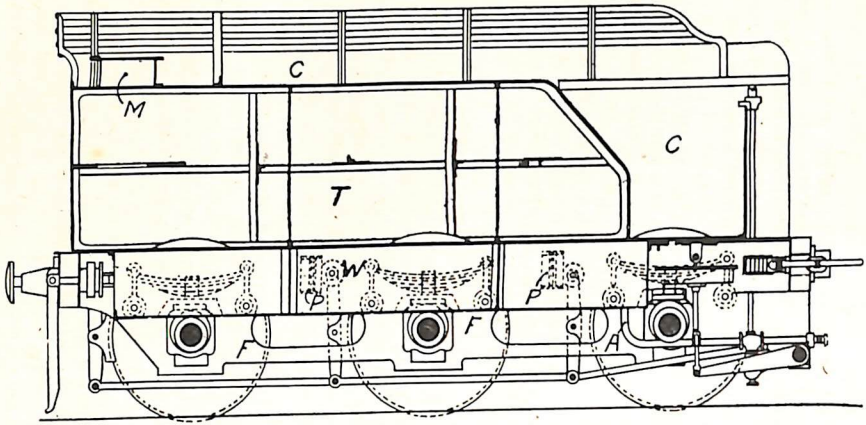

FIG. 25.—LONGITUDINAL SECTION OF TENDER.

irons, these cross stays being placed between the axles. The outer and inner frames on each side are also stayed together by plates and angle irons (P) placed midway between consecutive wheels. The connections serve as brackets for supporting the bottom of the tank, to which additional support is also given by longitudinal angle irons riveted to the top of the frames.

Tender axle-boxes differ from those previously described chiefly in that they are placed in the outside frame, and are therefore outside the wheels. The journals are at the ends of the axles, and the axle-boxes are closed in on the outside. The end covers are movable, so that the oil pads can be taken out and renewed when required without lifting the tender. The springs are generally on the top, and outside the frame, where they can be inspected. Formerly they were frequently placed inside the outer frame, and broken spring plates could not be seen.

There are many methods of coupling the tender to the engine, all of which are designed with a view to maintaining lateral steadiness between them when running. On the other hand, the connection must not be too rigid laterally, or excessive wear on the flanges of the wheels would result. The draw-bars have already been described, and in addition two buffers on the front of the tender bear against the back plate of the engine, being maintained in position by the buffer springs, which are under compression.

The top portion of the tender containing the tank T is independent of the framing. The bottom plate of the tank, about $\frac{3}{8}$ in. thick, is extended to the front to form the foot-plate or platform, and has a hinged plate attached to it, which can be let down to cover the gap between engine and tender. The sides of the tank are of $\frac{1}{4}$ in. plates, and the interior is strengthened by angle irons and stays. Transverse

plates to prevent the "back-wash" of the water are provided. Holes of sufficient size are made in these plates to allow a man to pass through when making repairs, and also to maintain a connection between the compartments. At the top of the tank, near the back of the tender, a man-hole (M) is provided, which also serves as the opening through which the tank is filled. This is furnished with a strainer to prevent bits of wood, dirt, etc., from entering the tank, and blocking the water pipes, the whole being covered with a lid. Another strainer with smaller holes is placed over the outlet to the water pipe A, which connects with the injector on the engine. Foreign matter getting into the cones of the latter would at once cause failure of the water supply to the boiler.

The plain tank above the tender framing would not, in most modern engines, provide sufficient water capacity without making the tender unduly high, and therefore a well (W) is usually added, which forms a narrower portion of the tank placed below the level of the platform between the two inner frames of the tender, and extending almost the length of the tank.

The coal space (CC) is at the front of the tender, and extends back on the top for about two-thirds of its length. It is generally made with a sloping bottom to allow the coal to descend gradually to the front, where the fireman can handle it.

The water connection between engine and tender is made by flexible pipes, or pipes with flexible joints, to allow for lateral and vertical movements. The pipes are usually metallic, with some form of ball and socket joint at the ends, and a sliding gland in the middle. Ordinary rubber or canvas pipes are not satisfactory, as it is usual to warm the water in the tender when standing, by means of steam from the boiler, and this causes the material of such pipes to perish.

Water Pick-up Apparatus.

This apparatus, illustrated in Fig. 26, was introduced in 1860, by Mr. John Ramsbottom, then chief of the locomotive department of the London and North Western Railway. It was about 25 years before any other railway applied this extremely useful invention, and then it was adopted by the Lancashire and Yorkshire Railway. The very

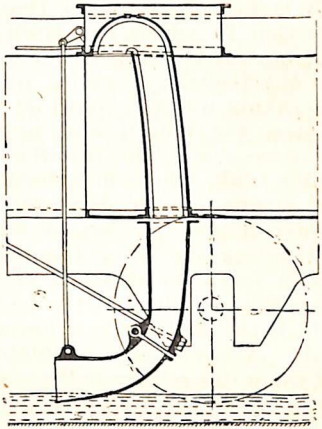

FIG. 26.—WATER PICK-UP APPARATUS.

large tenders which afterwards became necessary for long non-stop runs, finally caused several railways to take it up, and now it is in use on many of the largest main lines.

The troughs from which the water is taken are about 1 ft. 5 ins. wide by 6 ins. deep, and are placed between the rails at a suitable place where the line is perfectly straight and level. They are provided with automatic valves, whereby the water in them is maintained at constant level. The total length

of the troughs varies from 500 to about 700 yards, and at the ends, for about 70 to 80 yards, the bottom gradually slopes upwards. In order to prevent the end of the scoop on the tender from coming into contact with the trough at the ends, the gradient of the line is also made to suit the slope at the ends of the trough.

The scoop on the tender consists of a curved pipe which enlarges from bottom to top. The bottom portion which is bent forward so that its mouth faces the direction in which the train is moving, has a hinged joint so that this part of the pipe can be let down into the trough, or pulled up out of the way when not taking water. When let down ready for taking water, the hinged and upper portions form a continuous pipe. The top rises above the top of the water tank, where it is bent round in a semicircle and opens mouth downwards into the tank. The lower hinged portion, or scoop proper, has a thin steel cutting edge where it enters the water. A long rod with levers is attached to the hinged portion, and has a hand wheel at the foot-plate end, by turning which the fireman can lower the scoop into the trough. Above a certain minimum speed, the velocity of the water *relative to the scoop* produces sufficient energy to lift the water to the top of the pipe, whence it falls into the tank. At the end of the trough the scoop is raised clear of it, but should this be overlooked, the decreasing pressure of the water, as the tender runs up the gradient at the end, allows a balance weight to come into action, which automatically pulls the scoop up into its normal position.

During the operation, when the tank is full a hinged lid rises and allows the water to escape to an overflow, which is some cases is so arranged as to conduct this water back to the trough.

The lifting of the scoop out of the trough against the pressure of the inflowing water, especially at

high speed, is an arduous task, and modern tenders are usually supplied with means for lowering and raising the scoop mechanically. This is accomplished by a system of levers attached to the piston of a cylinder, worked either by steam or compressed air, or a vacuum cylinder may be used.

Many tank engines are fitted with a water pick-up apparatus, and since such engines have to run in both directions, two scoops are used, one facing forward and the other towards the back end of the engine. Both discharge into the same pipe.

The minimum speed at which water will rise from the trough into the tanks is from 15 to 20 miles per hour, and naturally varies with the height through which the water is to be lifted.

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